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SOVIET MICROPULSATIONS RESEARCH FOR POSSIBLE COMMUNICATIONS APPLICATION.

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SPECIAL TECHNICAL REPORT

SOVIET MICROPULSATIONS RESEARCH FOR POSSIBLE COMMUNICATIONS APPLICATION

by

James G. Beitchman

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13. ABSTRACT

This report reviews the fundamentals of high frequency geomagnetic micropulsations in the region of the electromagnetic spectrum from about 1-5 Hz. It then discusses, by reviewing the open literature, the large body of research performed in this discipline by Soviet scientists. Conclusions are not made as to whether or not the results of these investigations are, in fact, being applied towards functional communications systems. It is, however, demonstrated that the Soviet research is applicable and necessary to the possible future use of micropulsation modes for communications purposes.

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SUMMARY

In the first section of this work we review the state of knowledge of the generation and propagation of naturally occurring electromagnetic signals observed at the surface of the earth in the range of frequencies near 1Hz. Such signals are called high frequency micropulsations. We consider the applicability of these signal modes to strategic communications. We do not address the question of man-made generation of these signals, but stress the fact that the understanding of the generation and propagation modes of the naturally occurring disturbances is the most productive method of attacking the problem. In the second section we examine by means of open literature exploitation the Soviet programs of study in this area. We are able to conclude that the USSR sponsors an ambitious research program in this field -- perhaps the largest in the world. Although there is no direct evidence that the primary goal of this research is strategic communications, application of the results of these investigations to such communication systems can certainly not be ruled out. This would be especially true if the Soviet research is able to demonstrate the existence of additional low loss propagation modes for signals in this frequency range. The large scale networks of coordinated data collection stations which the Soviets maintain is the best hope of observing such modes.

/

1.0 INTRODUCTION

1.1 Purpose and Scope

The purpose of this volume is to examine, through surveying the open literature, the Soviet understanding of the small, extremely low frequency geomagnetic perturbations known as micropulsations, with a view toward their exploitation of this knowledge in strategic communications systems. As is well known, the penetrability of an electromagnetic wave into a conducting medium varies inversely with the frequency of the disturbance. (Figure 1.) Since the micropulsations reach the earth's surface in the form of electromagnetic waves, and since strategic messages are, by their definition, very terse, the exploitation of these extremely low frequency modes for communications purposes is not unreasonable. We do not here examine schemes for artificially generating such micropulsations for communications purposes.* In this work we attempt to examine the understanding of the generation, transmission, and propagation of the naturally occurring phenomena. Indeed, this understanding of natural phenomena would be the key to their exploitation in communications systems. We assume that the Soviets are fully aware of the state of research in the rest of the world. We will not conclude in this work whether, in fact, the Soviets are or are not working toward such a communications system. However, it can be stated *a priori* that the Soviets are certainly aware of the penetration depth and other arguments that favor the use of the lowest possible frequencies, consistent with the information to be transmitted, in strategic communications systems. Additionally, they are aware of the very low loss magnetohydrodynamic modes which exist in the tenuous plasma above the earth's atmosphere.

1.2 Micropulsations

What have come to be known as geomagnetic micropulsations are small fluctuations in the earth's magnetic field. These flucutations were

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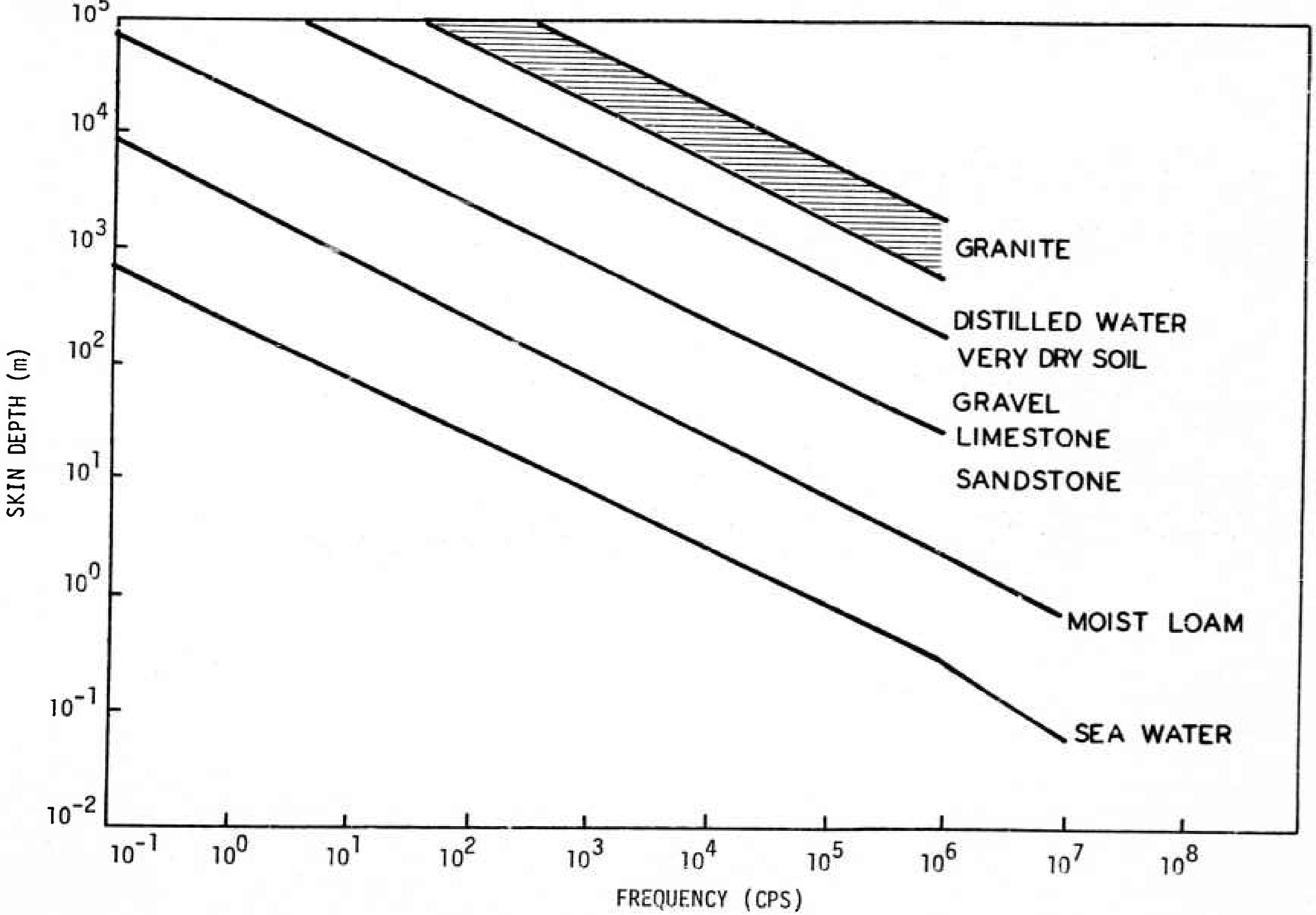
*A review of possible schemes of artificial generation (i.e., transmitters) of these phenomena has been completed recently by Fraser-Smith, et al.[1]

FIG. I

Skin Depth of E-M Radiation into Materials of Various Conductivity



first observed in 1861 by Stewart[2]. They are characterized primarily by the frequency (or frequencies) which makes up the disturbance. Since these frequencies are, at their highest, a few cycles per second, it is common to use period rather than frequency. The range of a period, T, for micropulsations is $T \sim 0.2$-600 sec. The amplitude of micropulsations is measured in gammas (γ) where $1\gamma = 10^{-5}$ oersted (Oe). The range of observed amplitudes is strongly frequency-dependent and varies from about 10^{-3} γ (often called 1 milligamma) to a few tens of gammas for the largest "giant pulsations." Recall that the earth's main field at the earth's surface ranges from 0.25 Oe (25000 γ) to 0.6 Oe (60000 γ), depending on geographic location. Micropulsations are, therefore, quite small compared to the earth's main or static field. In general, micropulsations propagate as magnetohydrodynamic waves in the tenuous plasma above the atmosphere. They propagate through the neutral atmosphere below the ionosphere to the ground as electromagnetic waves of various polarization.

In 1963 the International Association of Geomagnetism and Aeronomy (IAGA) recommended the adoption of a universal classification of micropulsations based on the fundamental period of the disturbance. This classification order is presented in Table 1 below.

TABLE 1

Classification of geomagnetic pulsations decided by IAGA at the 1963 Berkeley Meeting

Type		Period Range (sec)	Frequency (Hz)
Continuous pulsations	Pc1	0.2- 5	5-0.2
	Pc2	5- 10	0.2-0.1
	Pc3	10- 45	0.1-0.022
	Pc4	45-150	0.022-0.0067
	Pc5	150-600	0.0067-0.00017
Irregular pulsations	Pi1	1-40	1-0.025
	Pi2	40-150	0.025-0.0067

In this scheme the pulsation is classified in two main types: continuous - referring to a quasi-sinusoidal disturbance consisting of many periods of the same frequency, and irregular - those lacking a repetitive periodic nature.

Since a strategic communication message consists of a few tens of bits which must be transmitted in a time of not more than a few tens of minutes, it becomes apparent then that only the highest frequencies (Pc1 and Pi1) of micropulsations would be applicable for transmitting such messages. It is possible that messages of lesser consequence and hence shorter length, for example, to a submarine which would, say, "rise to the surface or near surface to receive a standard VLF message," might be achieved with fewer bits at lower bit rates than the strategic message itself. This would permit the use of lower frequency micropulsation channels. However, an incorrectly copied non-strategic message could result in missing the strategic message which was to be transmitted by more conventional means. For these reasons we will restrict ourselves to examining research on the Pc1 and Pi1 modes, and some other areas of research which may contribute to a better understanding of the high frequency micropulsation modes.

1.3 Pc1 and Pi1 Observations

In this section we shall discuss the characteristics of the experimentally observed micropulsations in the Pc1 and Pi1 frequency domain (0.2-5 Hz). The first observations of Pc1 were reported by Sucksdorf in 1936[3] under the nomenclature of "pearl necklace" signals. That these signals are aptly named is illustrated in Figure 2. The Pc1 signals are seen as evenly spaced bursts on the noise background. The bursts are spaced minutes apart and each one lasts about a minute. The bursts consist of field oscillations in the region of the Pc1 frequency range and have amplitude of about 0.01-0.1γ. One of the remarkable features of Pc1 pulsations is the extent to which the signal consists of one and only one frequency. The bandwidth may be as narrow as 0.1 Hz. This is shown in Figure 3 in which the spectral distribution of several Pc1

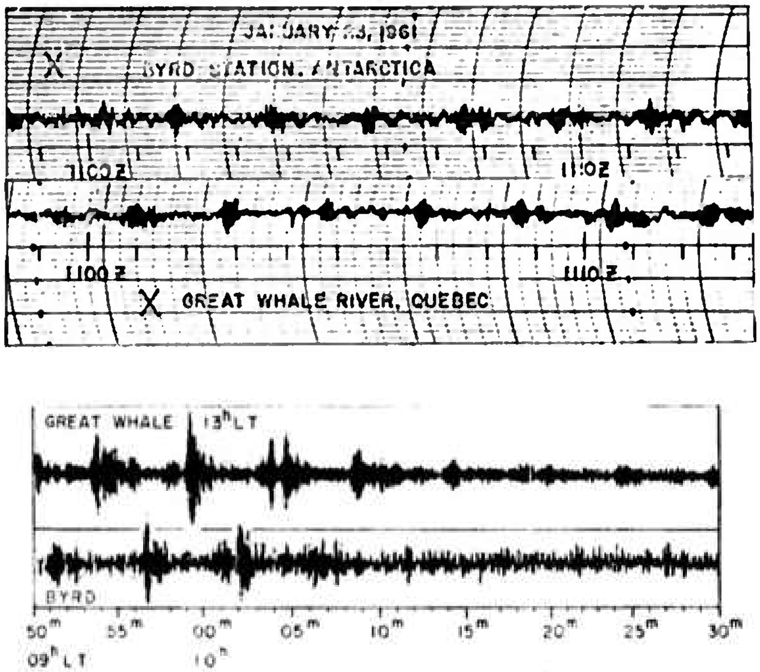


FIGURE 2

Two Pc1 "Pearl" Events Recorded at Conjugate Points
(After J. E. Lokken, J. A. Shand, C. S. Write; T. Saito)

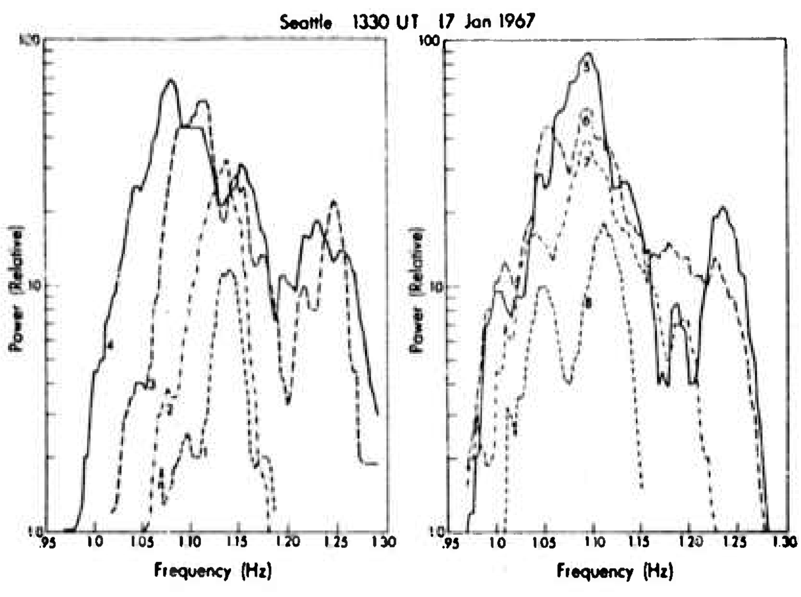


FIGURE 3

Power Spectra of Several "Pearls" in Pc1 Event
(After J. F. Kenney, H. B. Knaflich, H. B. Liemohn)

events is shown. There appears to be a relationship between the "pearl" spacing and the frequency of the signal within the "pearl." The spacing multiplied by the signal frequency is approximately constant, i.e., as the frequency falls the spacing increases. At some times the Pc1 signal appears to change frequency in a smooth fashion within each "pearl." This results in so-called "rising tones." Data on how the frequency changes with time are best displayed by using a device called a sonagraph. The device consists of a strip of unexposed film moving horizontally past a light beam which can vary in intensity and vertical position. The vertical position of the light beam on the film measures the frequency of the signal being recorded while the intensity of the beam (hence, the "blackness" of the developed film) represents the intensity of the signal. Sonagraphic data together with actual magnetograms represent the two most powerful tools in the experimental study of not only Pc1, but also of all other types of micropulsations. Figure 4 shows a sonagraphic record of Pc1 events consisting of consecutive "pearls" of rising tones.

A special case of rising tone pulsations is that in which the shape of the sonagraphic record changes from "pearl" to "pearl." The plot may "lean" more and more with each succeeding "pearl." An ideal picture of such a sonagram is shown in Figure 5. Such a signal is called a "hydromagnetic whistler" by analogy to "electromagnetic whistlers" seen at low VLF frequencies. Both types of "whistlers" signals are interpreted as wave packets bouncing back and forth between hemispheres along magnetic field lines, and both exhibit cut-off frequencies related to certain natural resonances found in the magnetosphere. The electromagnetic "whistlers" exhibit a lower cut-off frequency while the hydromagnetic "whistlers" have an upper cut-off frequency (2 Hz in the example shown in Figure 5). The VLF "whistlers" are so-called because they literally sound like descending whistling tones lasting several seconds when detected. The signal may undergo up to 50 detectable round trips along a geomagnetic field line between conjugate points. On each trip the rate of frequency change is modified by magnetospheric dispersive effects.

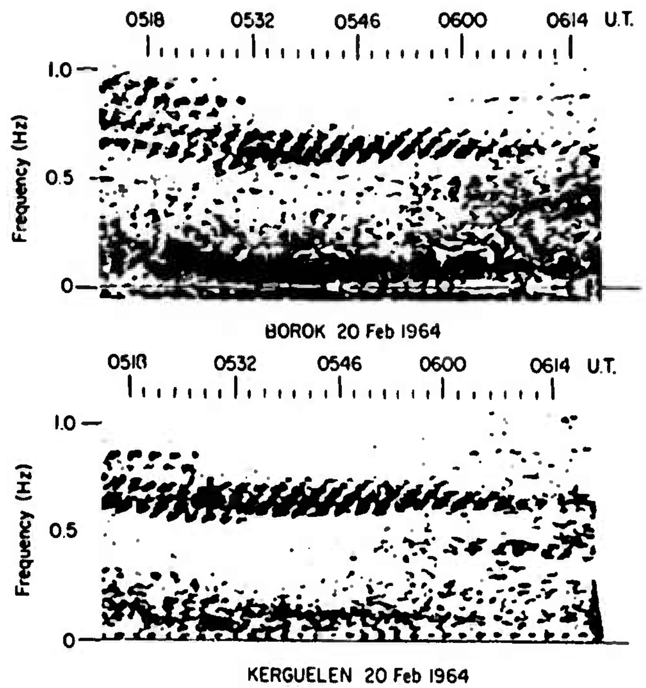


FIGURE 4

Sonagraphic Record of Pc1 Recorded at Near Conjugate Points
(After V. A. Troitskaya)

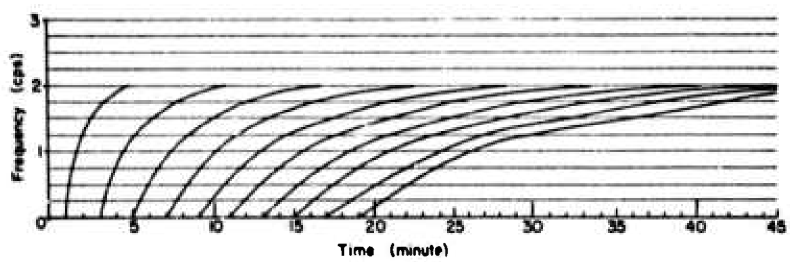


FIGURE 5

Schematic Sonagraphic Record of a Hydromagnetic Whistler
(After J. A. Jacobs, T. Watanabe)

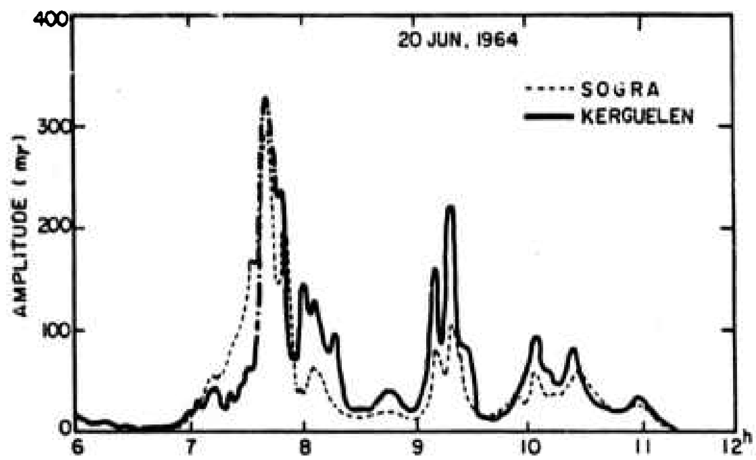


FIGURE 6

Amplitude of Pc1 Recorded Simultaneously at Conjugate Points
(After Lacourly, et. al.)

This causes a sonagraphic record of each detection to "lean" more on each succeeding bounce. We shall show in the following section how the theoretical picture of the magnetosphere supports this explanation.

Figures 2 and 4 illustrate another of the most important experimental facets of Pc1 observation. This is so-called "point conjugacy." Great Whale River, Quebec, and Byrd Station, Antarctica, of Figure 2 and Borok, U.S.S.R.*, and Kerguelen Island (in the Indian Ocean) of Figure 4 are pairs of approximate geomagnetic conjugate points. This means that they are at opposite ends of the same geomagnetic field line. As Figure 2 shows, the "pearl" bursts at Great Whale River occur nearly exactly between (in time) those received at the Byrd station conjugate point. This supports, in the general case of all Pc1 signals, the picture of wave packets traveling from hemisphere to hemisphere between conjugate points along magnetic field lines. This idea of field-guided waves in the magnetosphere is one of the principal results of the theory of magnetohydrodynamic waves which is used to explain all micropulsation phenomena. We shall exhibit this result in the following section. Many of the measured parameters of Pc1 exhibit conjugate behavior. This is strikingly illustrated by Figure 6 which shows the close correlation in amplitude of Pc1 signals recorded at conjugate points. Also, using the Sogra-Kerguelen conjugate stations, Gendrin[4] et al. established that the sense of rotation of Pc1 signals was opposite at conjugate points. They also established the 180° phase shift in amplitude between stations. These observations have proved crucial in distinguishing among various proposed theoretical models for the generation of Pc1 signals. Note that the sonagrams in Figure 4 show excellent correlation in the frequency content of Pc1 signals recorded at near conjugate points.

---

*Borok had for many years been the site of a geophysical observatory in the U.S.S.R. Shortly after the Kerguelen Station was established, a geophysical station was set up at the town of Sogra in the U.S.S.R. near Archangel. This site is closer to the exact conjugate point of Kerguelen than is Borok. The conjugate pair is most often referred to as Sogra-Kerguelen.

There has been much activity in correlating the occurrence and character of Pc1 "pearl" oscillations with various parameters. These parameters include magnetic activity, sun spot number, time of day, magnetic latitude, and ionospheric conditions. It is hoped that the establishment of such correlations will illuminate the generation and propagation mechanisms involved. Basically, what is found is that "pearl" oscillations are characteristic of a quiet or only weakly disturbed magnetosphere. It has been noted that the character of Pc1 changes drastically during conditions of magnetic disturbance.[5] These changes have been used by several authors as diagnostic tools for measuring the effects and intensity of the disturbance and in predicting its future course. We shall discuss this further when speaking of Pi1 events. Other results are that Pc1 "pearls" are most prevalent in the morning and evening at mid-latitudes and at midday at high latitudes (see the section on ionospheric effects for a possible explanation of the observation). Also noted is a frequency-dependence with latitude. The period of the signal within the "pearl" decreases with latitude. On a yearly basis, Pc1 activity seems greatest in the fall and winter months at mid-latitudes and at the equinoxes at high latitudes. Sun spot number affects the quality and quantity of Pc1 "pearl" events. All evidence seems to agree that Pc1 activity is at a minimum at sun spot maximum. It is not clear whether this is due to changes in the generation process in the far magnetosphere or in the propagation process which occurs near the earth in the ionosphere. At the Borok and Alma-Alta stations in the Soviet Union, maximum Pc1 occurrence was found[6] in the years between sun spot minimum and sun spot maximum, while Fraser-Smith[7] has deduced a purely inverse relationship between sun spot number and Pc1 activity. He claims that the peak noted at Borok is only a secondary maximum. It also appears that the regions of maximum Pc1 occurrence change with the 11-year solar activity cycle. In years of high sun spot number the maximum occurrence zone is located further south in the northern hemisphere than in quiet years. Fraser-Smith[8] has discovered a high correlation between the disturbed ionospheric condition known as "Spread F" and Pc1 occurrence. Spread F is related to field-aligned electron disturbances in the ionosphere and changes in the resulting electromagnetic character of the ionosphere which could result in increased leakage of Pc1 signals trapped in the ionospheric duct and, hence, increased observation of Pc1 on the ground. These data are, then, consistent with the theory of ionospheric Pc1 ducting which is presented in Section 1.5 of this report.

Before leaving Pc1 we should mention that there are other types of "continuous" magnetic activity observed in the Pc1 frequency domain. The most common is called "continuous emission" (CE) which on a sonagraphic record appears as one or more horizontal continuous bands occurring across a space up to several hours. Such emissions are generally of lower frequency than Pc1 "pearls" and it is not clear whether they are a separate entity or merely the highest frequency expression of similar CE signals which occur at Pc2 frequencies. Tepley and Amundsen[9], who have named the phenomenon, have noted that CE is more characteristic of disturbed magnetospheric conditions than are "pearls." They also find that CE is never observed at equatorial locations and that it is usually a nighttime phenomenon. It remains to be shown whether CE and Pc1 "pearls" have a common origin and similar propagation mechanisms.

The irregular micropulsations of high frequency, Pi1, are generally characteristic of the disturbed magnetosphere. This contrasts with Pc1 which is found under quiet conditions. As confirmed by records from Great Whale River -Byrd, and Sogra-Kerguelen, the Pi1 signals do exhibit point conjugacy. The frequency spectra as confirmed by sonagraphic analyses are far from monochromatic and usually contain broad continuous ranges of frequencies. In addition to being characteristic of disturbed conditions, the occurrence of Pi1 has been correlated with x-ray bursts reaching the earth's magnetosphere from cosmic sources. Each of the various types of Pi1 usually obeys its own pattern of development and disappearance. Most Pi1 signals are probably best thought of as "structured noise," that is, somewhere between pure noise and Pc1 continuous emissions. They have been classified in several categories.

L. R. Tepley[10] has identified one class which he calls "gurglers," since that is the sound heard if the tape on which the signals are recorded is played back 1000-2000 times faster than it was recorded. Occasional structured signals are seen superimposed on the background gurgle.

Gendrin and Lacourly[11] have delineated five categories of Pi1 disturbance:

1. Continuous noise. This signal is very similar to Pc1 continuous emissions. Its bandwidth, however, is much broader. It is centered around 0.2-0.3 Hz. There is no correlation with magnetic activity (disturbance).
2. Short irregular pulsations (SIP). These are broadband bursts of several minutes, often superimposed on a noise background. They may be repeated several times at intervals of 10-20 minutes. They have been recorded simultaneously within ±5 seconds at Sogra and Kerguelen.
3. Irregular pulsations of diminishing period or intervals of pulsations with diminishing period (IPDP). This disturbance is a high magnetic activity phenomenon and is properly best described as Pc1 + Pi1. It consists of a noise background plus a superimposed narrow-band signal whose frequency rises smoothly from about 0.5 Hz - 1.5 Hz in about thirty minutes. It is found in a very restricted geographic region between geomagnetic latitude 50^{o} - 65^{o}. It is thought to be associated with charged particle (probably protons) precipitation in the magnetosphere, and much work is underway to use it as a diagnostic tool in characterizing such precipitation events.
4. Irregular pulsations of increasing period (IPIP). This is a recently observed, rather rare phenomenon about which little is known.
5. Auroral irregular pulsations (AIP). This phenomenon is observed in the high latitude auroral zones during auroral disturbances.

As can be appreciated from the wealth and complexity of the various experimental records discussed in this section, the naturally occurring phenomena in the Pc1 range of the electromagnetic spectrum must be the result of quite complex mechanisms of generation and propagation. It is by no means clear that this listing of naturally occurring signals is as yet complete, nor have all of the measurable aspects of the known signal types been recorded. From this highly complex and incomplete data, it is hoped that accurate models of the magnetosphere may be constructed and that these models may yield information, such as new propagation modes, new methods of generating signals, etc., which may be applicable to the problem addressed in this study - the use of these modes for strategic communications.

In the next three sections we present what is by now the classic picture of micropulsation theory. Some of this classic theory is less than ten years old! We shall first present an outline of the magnetohydrodynamic wave picture of micropulsations at all frequencies. We shall then attempt to show that the very complex and, in general, insoluble wave and dispersion equations* do, in fact, have certain special cases which permit very simple and physical interpretation. These results are consistent with some, but not all, of the observations discussed in this section. In Section 1.6 we restrict ourselves to Pc1 signals and present the qualitative results of the theory of ionospheric wave guidance of Pc1 signals. This theory does much toward explaining the latitude, diurnal, and sun spot number dependence of Pc1 "pearls." In the last section, before proceeding to a review of the Soviet effort, we will review the "cyclotron instability theory" of the generation and amplification of Pc1 "pearls." This is the presently accepted theory which accounts for most of the observed details of the "pearl" phenomenon.

1.4 Magnetohydrodynamic Waves

The fundamental assumption concerning the nature of micropulsations is that they may be explained in terms of the generation and propagation of magnetohydrodynamic (MHD) waves in the cold, tenuous, two-particle (electrons and protons) plasma which inhabits the magnetosphere. In this section we shall, therefore, briefly review the fundamental principles and resulting equations on which the concept of magnetospheric MHD waves rests.

---

*Dispersion equations relate the allowed frequencies with their wavelength.

In 1942 Hannes Alfvén showed that in non-rigid conductors permeated by a constant magnetic field, B_o, hydromagnetic waves of a low enough frequency may propagate even though the attenuation of such waves is very great. The observation of such phenomena on a laboratory scale in columns of liquid metal or ionized gas is nearly impossible. However, because of its enormous dimensions and low density, the earth's magnetosphere is such that MHD waves can, in principle, propagate with extremely low loss. The velocity of propagation, V_A, of such a disturbance in a perfectly conductive, non-viscous, incompressible medium of density, ρ, permeated by a uniform magnetic field, F_o, is given by

$$V_A = (4\pi\rho)^{-1/2} B_o \qquad 1.4.1$$

and V_A is known as the Alfvén velocity, ρ is the matter density and B_o is the field strength. For a disturbance with a sinusoidal spatial and temporal variation, the relationship between frequency of this signal and its wave vector in this simple case of uniform field is given by

$$\omega = KV_A \cos\theta \qquad 1.4.2$$

where ω is the angular frequency in radians/sec ($\omega = \nu/2\pi$; ν = frequency in Hz), and K is the wave vector which is a vector pointing in the direction of propagation of the wave and having magnitude $|K| = 2\pi/\lambda$ (λ = wavelength in meters), θ is the angle between K and B_o. Thus, the velocity, ω/K, is given by $V_A\cos\theta$. In this simple approximation, the Alfvén wave is purely transverse. This means that plasma moves perpendicular to the direction of the wave vector and the disturbance in the magnetic field, B_o, is perpendicular to B_o. If the effects of plasma pressure are taken into account, other propagation modes appear, some of which may be compressional (i.e., acoustic) rather than transverse. These modes will in general have propagation velocities differing from the Alfvén velocity. It should be noted that for magnetospheric parameters the Alfvén velocity itself is on the order of hundreds of kilometers per second. This should be contrasted with the speed of light (3×10^5 km/sec) which is normally associated with electromagnetic wave propagation.

We shall now sketch the development of the set of equations needed to describe the propagation of MHD waves in the magnetosphere - a region of <u>non-uniform</u> field. We shall thereby relate the phenomena of <u>hydrodynamics</u> and <u>electrodynamics</u> in the magnetosphere through the equations of hydrodynamics and Maxwell's equations of electrodynamics together with certain reasonable assumptions. The electrodynamics of the problem is contained in equations 1.4.3-1.4.6, and the hydrodynamics of the problem is described by 1.4.7 and 1.4.8. In the magnetosphere, so-called displacement currents are negligible compared to conduction currents. Hence, one of the Maxwell equations becomes

$$\text{curl } B = 4\pi j/c \qquad 1.4.3$$

where B is the magnetic field strength, j the source current density, and c the velocity of light. Also, another of Maxwell's equations states

$$\text{div } B = 0 \qquad 1.4.4$$

and since charge does not accumulate anywhere, $dq/dt = 0$, q = charge density, the equation of charge conservation which is $dq/dt = \text{div } j$ implies

$$\text{div } j = 0 \qquad 1.4.5$$

If the medium is assumed to be a perfect conductor, then Ohm's law implies, in a medium moving with velocity, v, that the electric and magnetic field are related by

$$E = -v/c \times B \qquad 1.4.6$$

where E is the electric field.

The basic equation of hydrodynamics is

$$\rho\frac{dv}{dt} = j \times B/c \qquad 1.4.7$$

where ρ is the density of the matter present, and the sum of all non-electromagnetic external forces on the plasma is assumed to be much smaller than the electromagnetic force and is, therefore, neglected. Further, the medium is assumed to be incompressible which implies

$$\mathrm{div}\ v = 0 \qquad 1.4.8$$

From the above set of equations we now construct the wave equation which describes the propagation of small magnetic perturbations, b, in a constant but not spatially uniform field, B_0, (i.e., $B = B_0 + b$ where $|B_0| >> |b|$, or in other words, micropulsations are very small compared to the static magnetic field). Combining equation 1.4.3 and 1.4.7 with this assumption and assuming $|\partial v/\partial t| >> |(v\cdot \mathrm{grad})\ v|$ which assumption permits the replacement of a total by a partial derivative and results in mathematical simplification.

$$4\pi\rho\ \frac{\partial v}{\partial t} = -B_0 \times \mathrm{curl}\ b \qquad 1.4.9$$

We then arrive at the wave equation by taking the vector product with B_0 of the time derivative of 1.4.9, and

$$4\pi\rho\ (\frac{\partial^2 v}{\partial t^2} \times B) = -B_0 \times (\mathrm{curl}\ \dot{b}) \times B \qquad 1.4.10$$

Using the Maxwell equation for curl E and equation 1.4.6 to remove v and b, expression 1.4.10 finally becomes

$$-4\pi\rho\ \frac{\partial^2 E}{\partial t^2} = B_0 \times (\mathrm{curl\ curl}\ E) \times B_0 \qquad 1.4.11$$

This is the general vector expression written in terms of the varying fields themselves for MHD waves in a non-uniform magnetic field. J. W. Dungey[12,13] has shown that in spherical coordinates (R,θ,ϕ) and a dipole field*, $B_o = (B_R, B_\theta, 0)$ two modes which are in general coupled are excited.

The equation governing so-called poloidal oscillations is

$$\left\{\frac{4\pi\rho}{B_o^2}\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial R^2} - R^2 \sin\theta \frac{\partial}{\partial\theta}(\sin\theta)^{-1}\frac{\partial}{\partial\theta}\right\} R\sin\theta E_\phi$$

$$= \sin\theta\left\{B_R \frac{\partial}{\partial\theta} - B_\theta R\frac{\partial}{\partial R}\right\}(R\sin\theta)^{-1}\frac{\partial v_\phi}{\partial\phi} \qquad 1.4.12$$

The equation governing so-called toroidal oscillations is

$$\left\{\frac{4\pi\rho}{B_o^2}\frac{\partial^2}{\partial t^2} - \frac{1}{(R\sin\theta)^2}\left[(B_o\cdot\text{grad})(R\sin\phi)^2(B_o\cdot\text{grad}) + B_o^2\frac{\partial^2}{\partial\phi^2}\right]\right\}\frac{v_\phi}{R\sin\theta}$$

$$= -\frac{1}{(R\sin\theta)^2}\left\{\left(\frac{B_R}{R}\frac{\partial}{\partial\theta} - B_o\frac{\partial}{\partial R}\right)\left(R\sin\theta\frac{\partial E\phi}{\partial\phi}\right)\right\} \qquad 1.4.13$$

These two hideous coupled equations do, in fact, have as solutions all of the modes of reasonable models of the magnetosphere! Unfortunately, as is the case with many problems in electrodynamics, these expressions are not at all soluble in the general case, nor is it possible to apply intuition at this stage in order to understand a simple physical picture of the nature of the modes they describe. If, however, one makes the assumption of axial or cylindrical symmetry, mathematically: $\partial/\partial\phi = 0$, then the modes "decouple," greatly simplifying the interpretation of the equations. The results of this assumption are that the poloidal

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*97% of the real earth's field may be represented by a dipole. The remaining 3% is usually expressed as a series of higher order spherical harmonic terms. Many of the theoretical treatments of the micropulsation problem employ only the dipole approximation to the field.

oscillation equation governs the field and velocity components

$$(0,0,E_\phi);\ (b_R,b_\theta,0);\ (v_R,v_\theta,0) \qquad 1.4.14$$

and the toroidal oscillation equation governs remaining components

$$(E_R,E_\theta,0);\ (0,0,b_\phi);\ (0,0,v_\phi) \qquad 1.4.15$$

A simple physical picture of the allowed modes now emerges. This division implies that the toroidal oscillation modes can be interpreted as propagating along the lines of force of the field and one may speak of "oscillations of the lines of force." Most of the progress that has been made in understanding the longer period (Pc2 to Pc5) micropulsations has involved solutions of the toroidal oscillation modes. The wavelengths of these long wave modes are characterized by the dimension of the magnetospheric cavity. On the other hand, the poloidal modes represent propagation across the lines of force. It is not yet clear that examination of the poloidal modes of this approximation has yielded much progress in the understanding of real micropulsations. It should be noted that the simplifying assumption of axial symmetry is rather strong and unphysical since it implies that the disturbances occur in-phase and simultaneously over the whole earth - a point at variance with experimental facts.

With the aid of numerical (computer) techniques some of the restrictive original assumptions, such as uniform plasma density, have been removed by some workers. We should point out here that all the waves derived by these techniques must pass through the ionosphere between 80 and about 500 km altitude and undergo the transition from MHD waves to EM waves before they are detected at the ground. As will be described below, the earth-ionosphere cavity acts as a filter which imposes its own resonance structure on the spectrum of the impinging MHD waves. Thus, the observed frequency spectrum reflects the characteristics of this filter as well as the characteristics of the magnetosphere above this filter. In addition, the ionosphere itself has the characteristics of a waveguide at Pc1 frequencies and is responsible for the propagation of these signals from high to low latitudes. In this way the observed frequency spectrum of Pc1 may reflect the effect of waveguide-like, cut-off frequencies.

In addition to the allowed modes described by equations 1.4.12 and 1.4.13 it has been possible to calculate the dispersion relationship for a reasonable approximation to the magnetosphere. This is the relationship between the allowed frequencies and the wavelength of the disturbance. The resulting expressions are analogous to equation 1.4.2, the simple dispersion relationship for a uniform field. The three major assumptions here are:

1. The magnetosphere consists of "cold" (zero temperature) plasma in which the constituents, protons and electrons, are motionless in the unperturbed state. The adoption of such a model leads to sharp resonances but does not otherwise greatly alter the results.
2. All loss mechanisms including collisions between particles are neglected. This is a reasonable assumption in view of the very low average density of particles - approximately $10/cm^3$.
3. The perturbations of the field are small compared to the main field itself. This is quite a reasonable assumption since, as we have said, the main field is about 30000 γ while at their very largest, micropulsations are about 100 γ.

Under these assumptions the dispersion relationship is

$$\tan^2 \theta = - \frac{P(n^2 - R)(n^2 - L)}{(Sn^2 - RL)(n^2 - P)} \qquad 1.4.15$$

where n is the index of refraction $|n| = c|k|/\omega$, and θ is the angle between B_o, the static field, and k, the propagation vector ($|k| = 2\pi/\lambda$, λ = wavelength).

The expressions for P, R, L, and S contain the frequency dependencies, and

$$R = 1 - \sum_j \frac{\Omega_j^2}{\omega^2}\left(\frac{\omega}{\omega + \varepsilon_j\omega_j}\right) \qquad 1.4.16$$

$$L = 1 - \sum_j \frac{\Omega_j^2}{\omega^2}\left(\frac{\omega}{\omega - \varepsilon_j\omega_j}\right) \qquad 1.4.17$$

$$P = 1 - \sum_j \frac{\Omega_j^2}{\omega^2} \qquad 1.4.18$$

$$S = 1/2\ (R + L) \qquad 1.4.19$$

where $$\omega_j = \left|\frac{e\,B_o}{m_j c}\right| \qquad 1.4.20$$

$$\Omega_j = \frac{4\pi n_j e^2}{m_j} \qquad 1.4.21$$

where ω is the angular frequency in radians/sec of the signal and the sum over j means there are two terms in 1.4.16 through 1.4.18, one for electrons and one for protons, i.e., $\varepsilon_j = 1$ for the proton term and $\varepsilon_j = -1$ for the electron term; $m_j = m_p$, the mass of the proton for the proton term, and $m_j = m_e$, the mass of the electron for the electron term. n_j is the number density of each of the particle types. If we assume total charge neutrality, then $n_e = n_p$. ω_j is called the cyclotron frequency of each of the particle types, and Ω_j, the plasma frequency.

If we look in the directions of interest in the simplified mode equations (the ones obtained by assuming axial symmetry), then we also find great simplification and physical meaning in the dispersion relationship. In the one case, $\theta = 0^o$, propagation <u>along</u> the lines of force (the toroidal case)

$$n_R^2 = R \qquad \text{and} \qquad n_L^2 = L \qquad 1.4.22$$

These are two wave modes, one right circularly polarized (n_R^2) and the other left circularly polarized (n_L^2). These simple relationships exhibit resonances at the cyclotron frequencies of the electron and proton and, as we shall see below, these resonances are reflected in experimental observations. Transverse propagation (θ = 90°; poloidal modes) yields

$$n_x^2 = \frac{2RL}{R+L} \qquad \text{and} \qquad n_o^2 = P \qquad 1.4.23$$

which have the characteristics of ordinary (n_o^2) and extraordinary (n_x^2) waves familiar in the propagation of electromagnetic radiation through regions of magnetic field permeated plasma. These relationships exhibit lower cut-off frequencies related to the plasma frequencies Ω_p and Ω_e in the manner of, for example, high frequency radio waves encountering the ionosphere.

Jacobs[14] gives some numerical examples of the frequencies involved in these dispersion relationships. The example is for a region of the magnetosphere which may be significant in the generation of Pc1. At a magnetic equatorial distance of L = 5.6* the magnetic field is $B_o \approx 170\ \gamma$ and $n_e = n_p = 10\ cm^{-3}$. The relevant plasma and cyclotron frequencies are

For protons

$$\omega_p/2\pi = 2.6\ \text{Hz}$$

$$\Omega_p/2\pi = 6.5 \times 10^2\ \text{Hz}$$

*The value of L is, in the dipole field approximation, the distance in earth radii to a point in space above the magnetic equator. In an axially symmetric dipole field a given value of L designates a set of field lines all of which have the same magnetic equatorial distance from the dipole source. This set of lines may be pictured as forming a toroidal shell centered at the dipole and having a maximum distance (in earth radii) of L from the dipole at the equator of the field. Charged particles of a given energy have their motion confined to such a shell. In the real field case (97% dipolar, 3% non-dipolar) the L value is defined in terms of a so-called mathematical invariant of the magnetic field and the loci of constant L no longer exactly conform to magnetic field shells. However, deviation is on the order of only 1% so that the simple intuitive picture of L = constant describing magnetic field shells may be retained as a good approximation to reality. In Figure 7 the concept of L-shells is dramatically illustrated using three low energy proton belts. Figure 8 shows the intersection of contours of constant L with the surface of the earth. These contours are generated from a 99 term series expression for the field. It does not include the effects of the distortion introduced by the solar wind, hence, it is not a true representation beyond L ~ 6. See Figure 18 for a picture of the solar wind distortion.

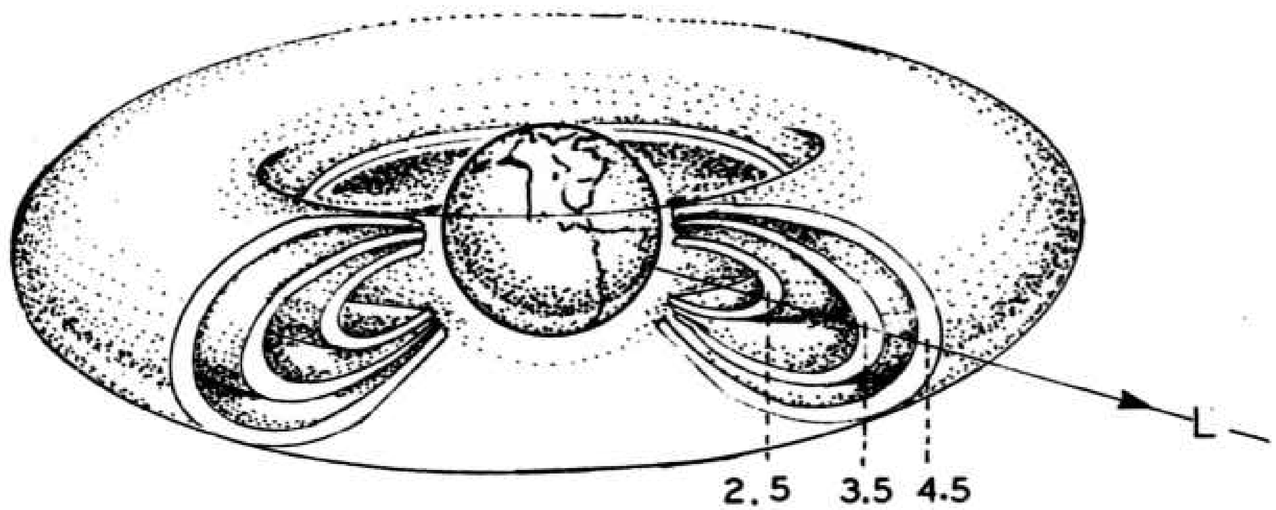

Fig. 7

The three low energy proton belts which form shells at L = 4.5, 3.5 and 2.5. The lowest energy protons are at high L-number, while the high energy protons are close in. In reality the belts join more smoothly to each other than the drawing would indicate.

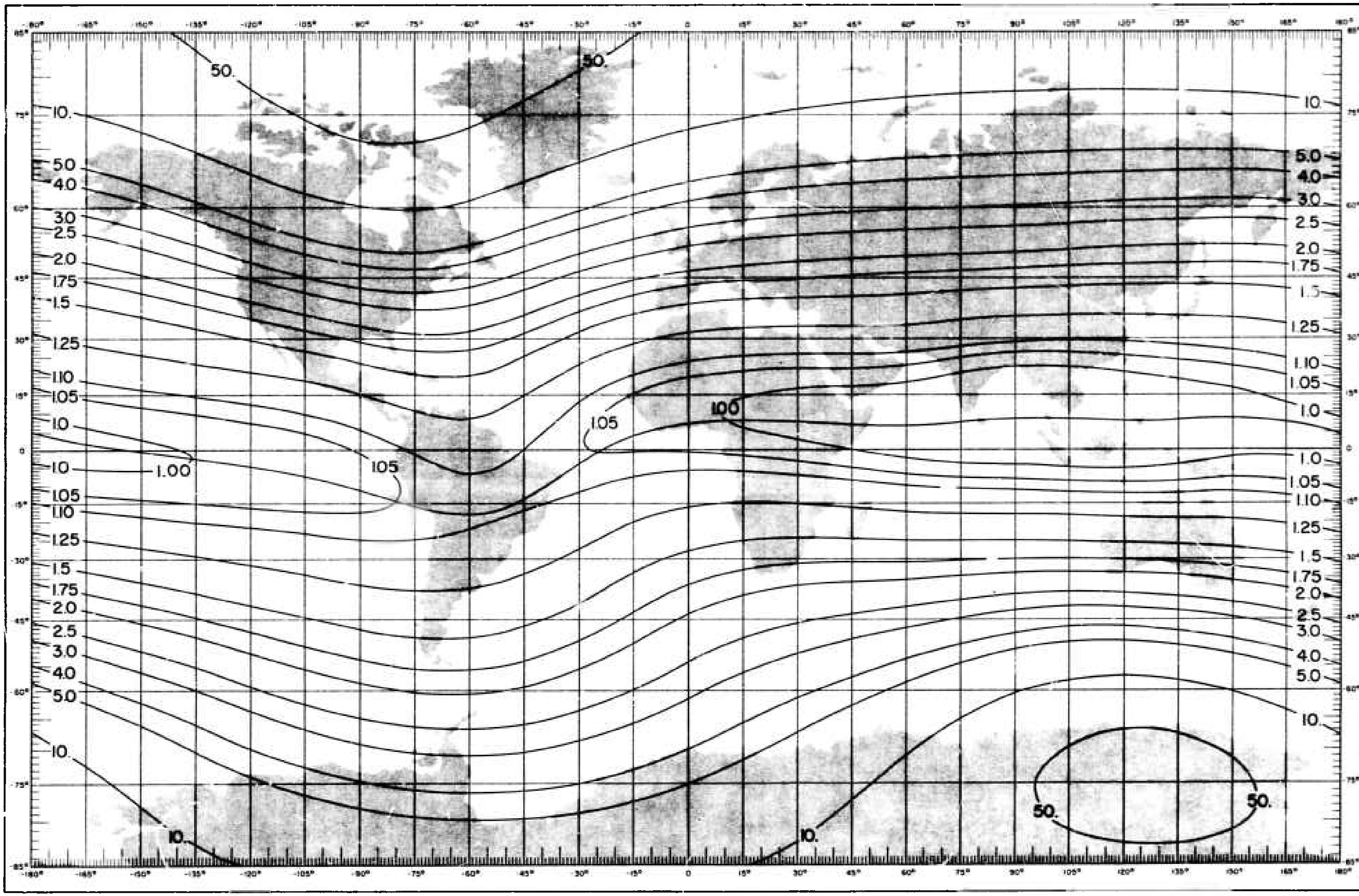

FIGURE 8

Intersection of L-Shells with the Surface of the Earth (After E. G. Stassinopoulous)

For electrons

$$\omega_e/2\pi = 4.8 \times 10^3 \text{Hz}$$

$$\Omega_e/2\pi = 2.8 \times 10^4 \text{Hz}$$

If one takes the theoretical results of J. M. Cornwall[15] which indicate a critical frequency, ω, for amplification and propagation (i.e., a frequency above which propagation and amplification can not take place)

$$\frac{\omega}{\omega_j} \sim 0.5 - 0.6$$

where ω_j is some equatorial value of the cyclotron frequency, and if one uses $\omega_j = \omega_p = 2.6$ Hz, the proton cyclotron resonance frequency quoted above, then we find agreement with the experimental fact that the maximum observed frequency in Pc1 is about 1 Hz (i.e., about 2.6 times 0.5). Here the proton cyclotron resonance acts as an upper cut-off frequency analogous to the more well understood effect of the electron cyclotron resonance. The higher frequency electron resonance (10^3 - 10^4 Hz) is responsible for the frequency cut-off of magnetic field guided "whistler" electromagnetic signals which are seen at audio frequencies ($\sim 10^3$ Hz). Likewise, the lower frequency proton cyclotron resonance may be responsible for the class of Pc1 signals which look like "hydromagnetic whistlers" in the sub 1 Hz spectral region. The upper cut-off frequency shown in Figure 5 (in that example it is closer to 2 Hz) is a direct consequence of the proton cyclotron resonance as is the increased "leaning" of the sonagraphic signal.

The dispersion relations have their primary use in addressing what is generally called the "diagnostic" problem. This area concerns the problem of using the spectral and temporal characteristics of micropulsations as quantities which convey information about the state of space near the earth. Such parameters as the plasma density, the character and quantity of the particle precipitation reaching earth from the sun, and the state of geomagnetic activity may be studied through micropulsations. All affect the character of micropulsation signals through the dispersion equations. This can be seen most obviously in the case of plasma density through the plasma frequencies, Ω, which appear in the dispersion relationship. As Equation 1.4.21 shows, Ω is directly proportional to the plasma particle density. Analysis of the dispersion relationship yields methods of extracting the plasma density profile from micropulsation signals, as well as localizing the region of space in which the micropulsation was generated. Thus, in the view of many micropulsation researchers, micropulsations may be thought of as the world's cheapest space probes, since they can convey complex information about space to the surface of the earth. We should add here that there is some conflict among investigators concerning whether the indirectly derived "space information" from micropulsation dispersion analysis is entirely accurate. As an example, Heacock[16] has shown that while dispersion techniques yield distances of L = 6-7 for the generation region of structured Pc1 signals (i.e., those which are hydromagnetic whistlers or are rising tone disturbances, as in Figures 4 and 5); direct observation by the Ogo 3 and 5 satellites indicates a generation region much closer to earth at L = 4-5. In this case, not only is it a simple case of different distance results, but more importantly that these two locations are in distinctly different plasma regions of near-earth space.

1.5 Ionospheric and Other Resonance Effects

As we have previously stated, the effect of the ionosphere and the neutral atmospheric cavity below it is twofold. First, it acts as a filter imposing its own set of structures on the MHD waves generated in the far reaches of the magnetosphere, and secondly, the ionosphere layer itself may act as a wave guide for the shortwave Pc1 excitations. We shall consider these effects separately.

The filter-like effects of the ionosphere are usually treated by calculating power spectrum at ground level or transmission coefficients of the ionosphere. Such calculations are usually performed over the entire range of micropulsation frequencies from 10^{-4} to 10^{0} Hz. The attempt is to construct models which exhibit resonances corresponding to the observed peaks in the frequency spectra of micropulsations. Unfortunately, the experimental situation is not clear enough so that it is possible to distinguish with certainty between the various theoretical models. The Soviet authors Dubrovsky and Kramarenko have made[17] a compilation of some existing ground based experimental spectral data (Figure 9). As can be seen from the variability of this data from observatory to observatory, the location of the fine structure peaks is not entirely unambiguous! One can deduce that the background changes by about 6.3 db/ octave from 10^{-4} to 10^{-2} Hz and 9.9 db/octave from 10^{-2} to 1 Hz. The filter effect itself is quite apparent if one compares the spectral densities of Figure 9 for ground-based observation with those of Figure 10 which were compiled from satellite data above the ionosphere and, hence, are without filtering. Attempts to calculate such spectra have used several different mathematical approaches and physical models. Among the more successful is the work of Prince and Bostick.[18] The results of their calculations are displayed in Figure 11. The model was that of waves vertically incident on the ionosphere at the magnetic equator (perpendicular to the magnetic field). In their model they use a uniform flat spectrum for the incident wave and, thus, ignore the generation spectrum effects of the solutions of the poloidal-toroidal equations of the previous section. They use a model of the ionosphere based on a time of sun spot minimum. It is interesting that even with these restrictive assumptions they obtain a 9 db/octave background slope in the 10^{-2} - 10^{0} Hz region. This agrees with the experimental observations quoted above. One important result of their work is that the region of the lower exosphere (<2000 km) above the ionosphere plays an important role in determining these spectra. In this region the Alfvén velocity reaches a maximum value. This recognition has been the basis of a series of papers by Field and C. Greifinger[19, 20], P. and C. Greifinger,[21] and P. Greifinger[22] in which they employ a layer structure consisting of

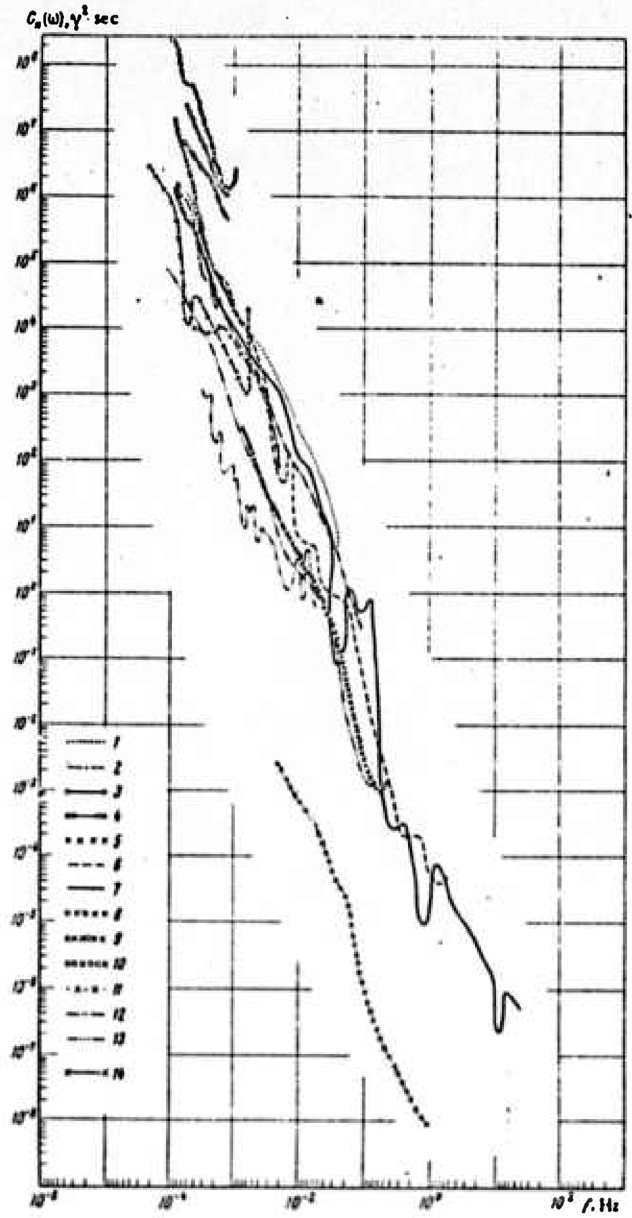

FIGURE 9

Power Spectrum of the Magnetic Field as Observed at 14 Separate Ground Stations Scattered Around the World (After V. G. Dubrovskiy, S. A. Kramarenko)

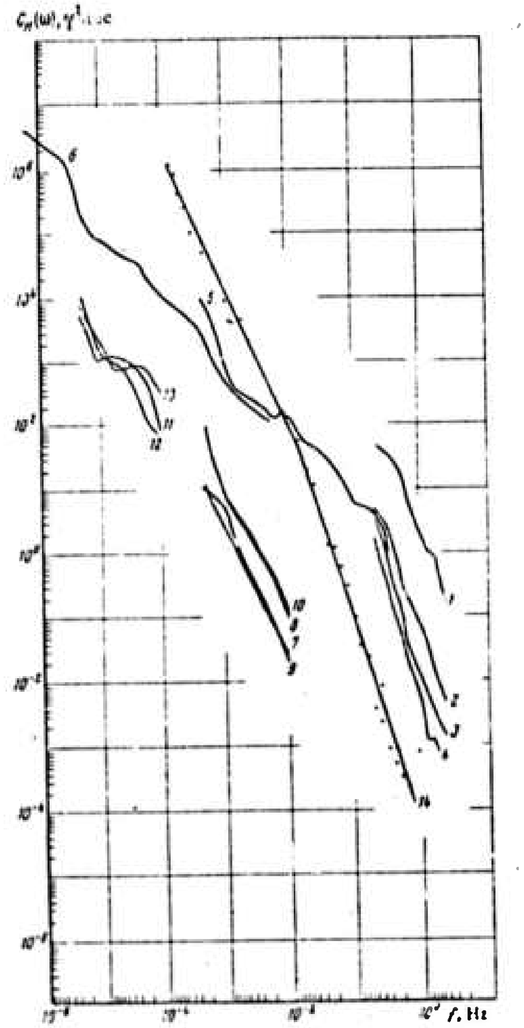

FIGURE 10

Power Spectrum of the Magnetic Field
As Described in Various Satellite Measurements
(After V. G. Dubrovskiy, S. A. Kramarenko)

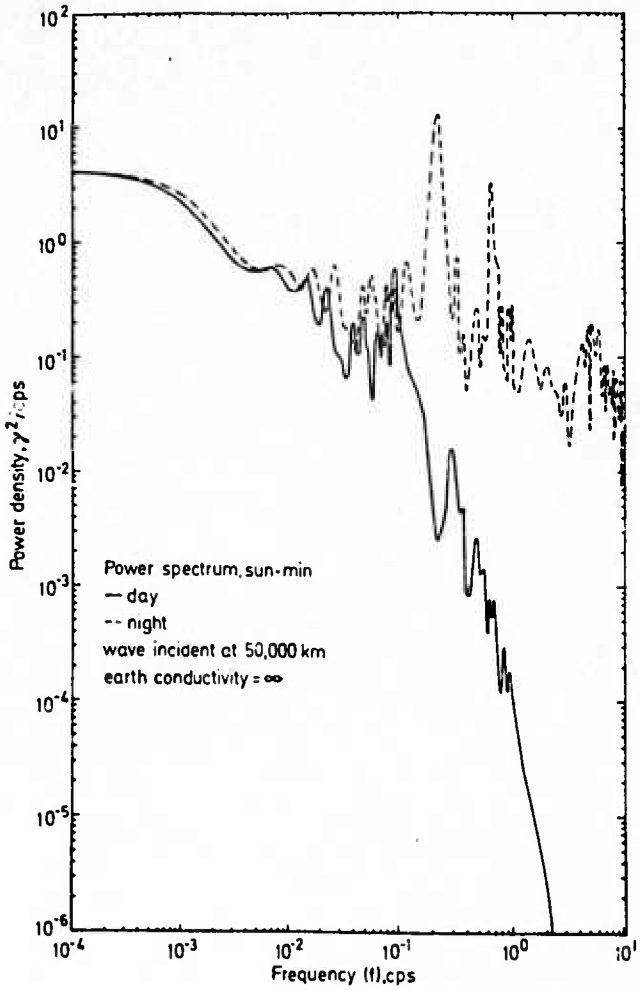

FIGURE 11

Computed Power Spectrum for Sun Spot Minimum
(After C. E. Prince, Jr., F. Bostick, Jr.)

1. a perfectly conducting (reflecting) ground (0 km)
2. an earth-ionosphere cavity (0 to 80 km)
3. an ionosphere (80 km to 400-500 km)
4. a lower exosphere of variable Alfvén velocity (400-500 km to 1500-2000 km)
5. all above 1500-2000 km

The variation in the boundary locations accounts for local time of day and sun spot number. The model includes the lossy effect of particle collisions in the ionosphere region. Their calculations determine the transmission coefficients of such a structure. The kinds of results they obtain are shown in Figures 12 and 13. Note that the structure in their results is primarily a result of the lower exosphere layer rather than the ionosphere layer. The Pc4 pulsation resonance (the far left-hand peak in Figure 12) alone is a function of the ionosphere while all of the higher frequency resonances (Pc3 to Pc1) are the results of the lower exospheric layer. The series of papers treats various angles of ionospheric incidence and angles between propagation vector and magnetic field.

An important addition to the understanding of those factors which contribute to the resonance spectrum of micropulsations was contributed by A. K. Sen in 1968.[23,24] Sen showed the extreme sensitivity of the spectrum to the path <u>length</u> taken by the signal from the generation region near the distant magnetospheric boundary to the top of the ionosphere. Since the dimensions of the magnetospheric cavity are strongly related to the solar wind, this mechanism may account for the changes of period of micropulsations which occur with changes of solar activity. The resonances found by Sen are remarkably sharp. They appear at 935, 311, 134, 103, 11, 6 and 2.5 sec. He claims that the resonances are of such high Q (he uses a transmission line analogy to solve the problem) that they completely mask all lower exospheric

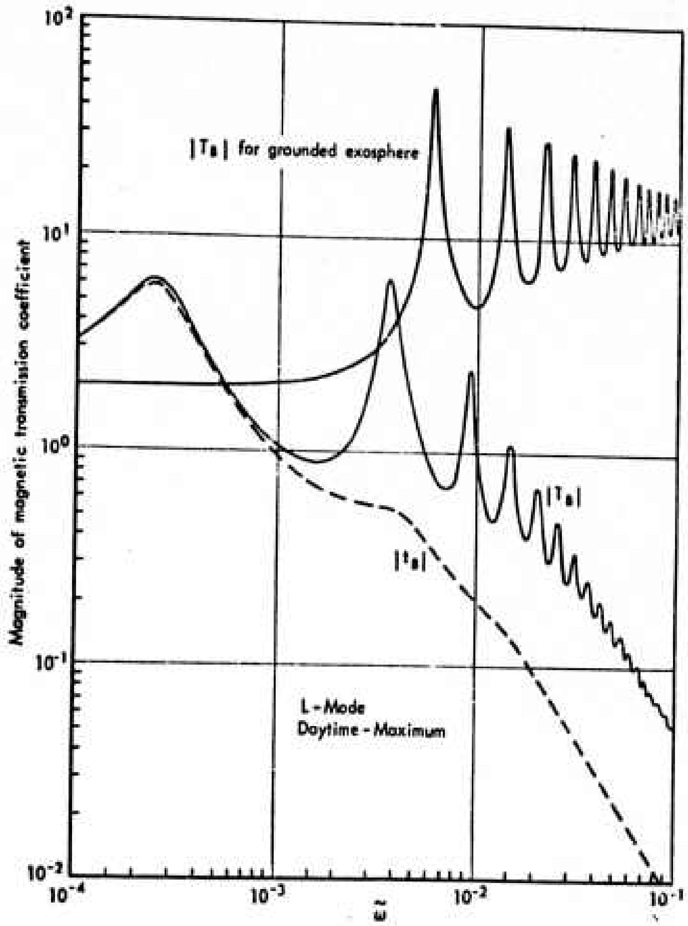

FIGURE 12

$|T_B|$ Is the Composite Magnetic Transmission Coefficient for Daytime Sun Spot Maximum; $|t_B|$ Is the Ionospheric Transmission Coefficient Alone (After E. C. Field, C. Greifinger)

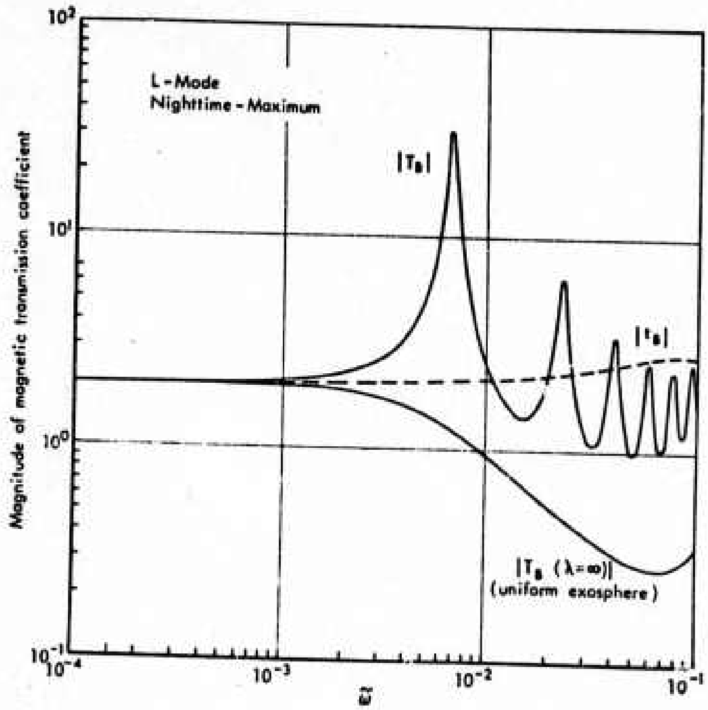

FIGURE 13

$|T_B|$ Is the Composite Magnetic Transmission Coefficient for Nighttime Sun Spot Maximum; $|t_B|$ Is the Ionospheric Transmission Coefficient Alone (After E. C. Field, C. Greifinger) and ionospheric effects. The resonances are, in fact, so sharp that they could account for the monochromatic (i.e., single frequency sinusoidal) nature seen in all the continuous micropulsations, Pc1-5.

As can be seen by the three examples cited above and the variability of the experimental data, the understanding of the resonance effects of the ionosphere and exosphere is far from complete.

The other major effect of the ionosphere is the ducted propagation of Pc1 signals. One must keep in mind that because of its short wave length compared to other micropulsation modes, Pc1 signals may be treated by methods of geometric optics and may be visualized more in terms of the propagation of wave groups rather than as gross global excitations of the magnetospheric cavity - the "picture" of Pc2-5. It is generally agreed that the generation mechanism of Pc1 is in the region L = 4-10, the L-shells of which intersect the surface of the earth between magnetic latitudes $\pm 60^\circ$ to $\pm 72^\circ$, and thus the left-hand circularly polarized, field-guided Pc1 signals reach the earth at these points. Experimental evidence indicates, however, that Pc1 may be observed almost simultaneously from the auroral zone to the equator along a magnetic longitude while the longitudinal propagation (across the earth perpendicular to the longitude) appears to be highly restricted.* The mechanism of ducted propagation within the ionosphere is thought to be the guidance of the signals about the region of maximum electron density in the F_2 region of the ionosphere. The signal, after being transformed to right hand circular polarization, travels both north and south along the geomagnetic longitude within the duct centered about the density maximum. The propagation is pictured schematically in Figure 14. The signal reaches the ground at lower latitudes because of leakage from the duct. This model by R. N. Manchester[26] succeeds in explaining several of the experimentally observed characteristics of Pc1. The first is the low frequency cut off for Pc1 at about 0.5 Hz.

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*A recent very interesting paper by Campbell and Thornberry[25] appears to contradict this statement about longitudinal Pc1 propagation. Stations widely separated in longitude - Hawaii, Alaska, Washington, Colorado, and Quebec - recorded the apparent longitudinal propagation of two Pc1 events. The propagation was westward from a generation region determined to be over the eastern United States. The longitudinal propagation velocity was found to be 2.3 x 10^3 km/sec - a very high number compared to usual ionospheric duct values. Because of this high velocity, it is possible that some mechanism other than ionospheric ducting could be responsible. In any case, much more experimental evidence needs to be gathered in order to understand this new data.

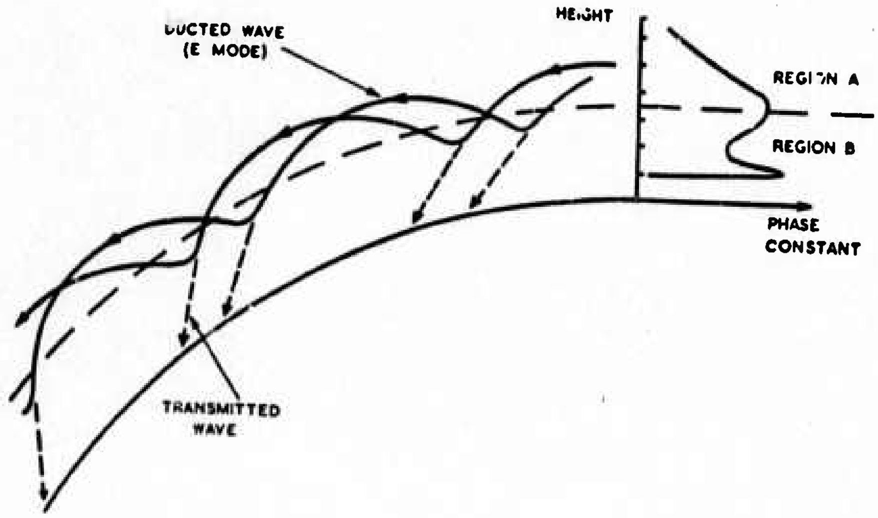


FIGURE 14

Schematic Representation of the Ionospheric Ducting of Pc1 Signals from High to Low Latitude
(After F. N. Manchester)

Manchester's model yields three propagation modes for the waveguide, as is shown in Figure 15. The lowest possible frequency of propagation is about 0.45 Hz, which is in excellent agreement with the observed cut-off at 0.5 Hz. The second experimental realization of the Manchester theory is illustrated in Figure 16. Shown is the variation in duct attenuation with local time of day. This is due to diurnal changes in the character of the ionosphere. The poor efficiency of the duct at local noon is realized experimentally in the fact that the occurrence of Pc1 at mid-latitudes is rare at that time of day. Further experiments by Manchester and Fraser[27] serve to confirm this statement. They found that the coincidence of occurrence of Pc1 at two latitudinally separated stations (Hobart and Newcastle) is much greater at night when the duct is more efficient than during the day. Further, the lowest observed frequency in a simultaneously observed signal only very rarely was less than the predicted theoretical lowest cut-off frequency calculated from real-time measurements of the critical reflection frequency and, thus, the state of the ionosphere. This is illustrated in Figure 17. Several attempts have been made to measure the propagation velocity along the longitude. R. C. Wentworth[28] obtained a value of 900 km/sec using data between College, Alaska, and Kaui, Hawaii. Manchester[29] measured the time correlation of signals between Hobart and Newcastle. He found that the propagation velocity toward the equator (Hobart to Newcastle) was approximately equal to the Alfvén velocity at 340 km altitude. Both of these results are in agreement with the velocities shown in Figure 15.

As with much of the experimental data in this field, there is also a body of experimental evidence which contradicts the above studies. Campbell and Siltner[30] and Campbell[31] found little signal coherency at stations separated by 1000 km. Heacock et al.[32] found that in the summer months, stations in Finland separated by only 6^{o} of latitude rarely observed simultaneous Pc1 signals. The discrepancies between these various sets of data is not well understood.

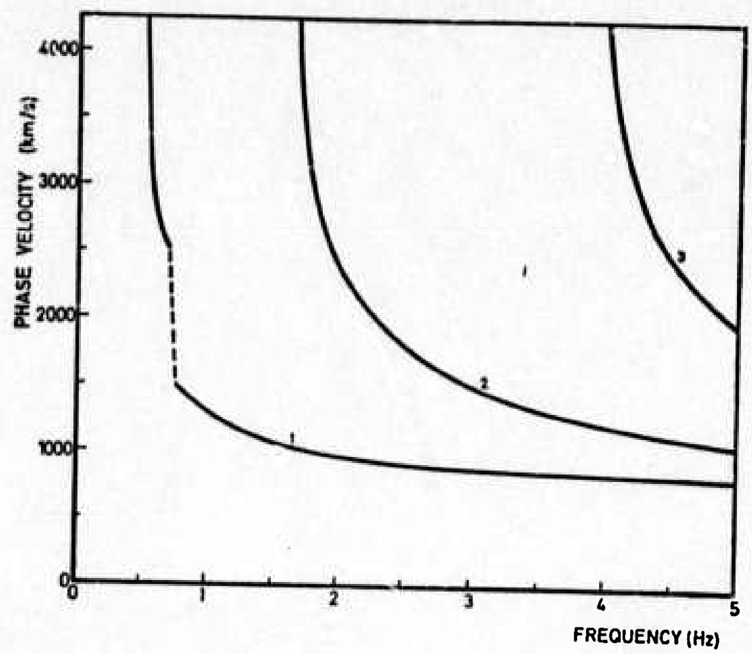


FIGURE 15

The Three Modes Resulting from Manchester's Model of the Pc1 Ionospheric Duct
(After F. N. Manchester)

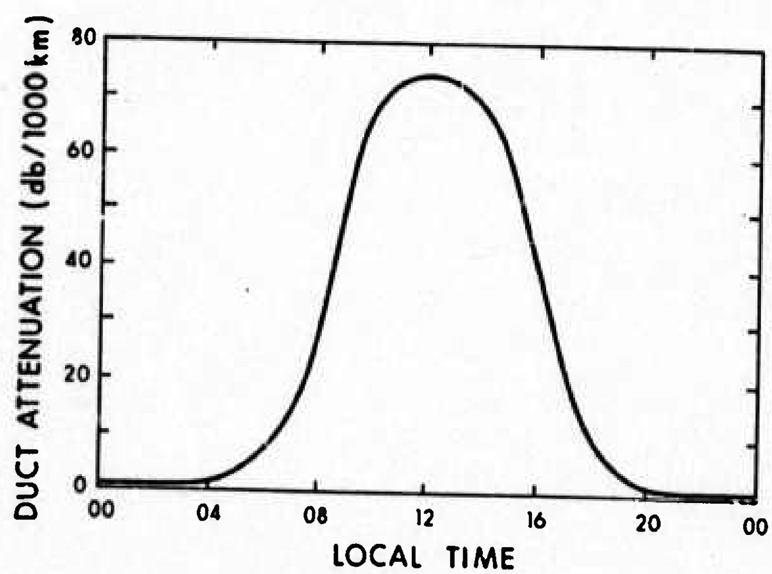


FIGURE 16

Diurnal Variation of Pc1 Ionospheric Duct Attenuation at 3 Hz in the Manchester Model
(After F. N. Manchester)

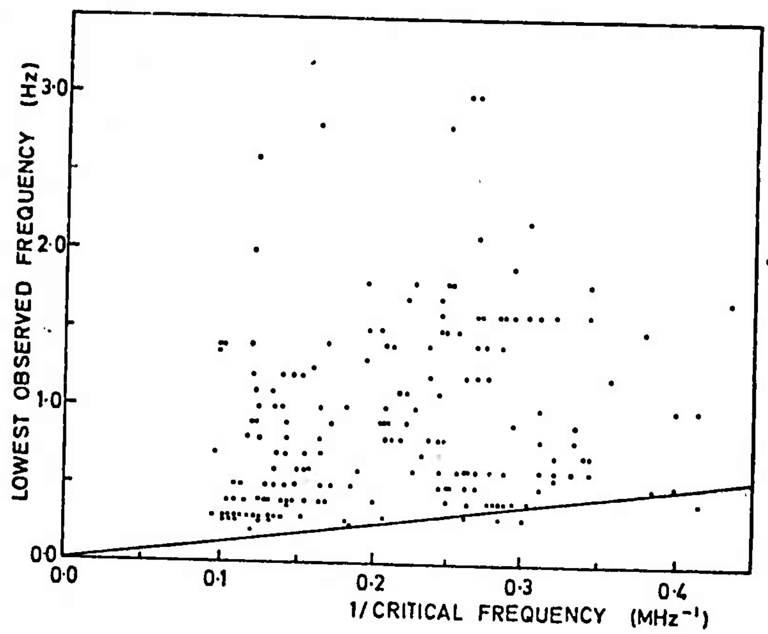


FIGURE 17

Lowest frequency observed at Hobart, Australia during each hour when activity was present plotted against the reciprocal of the corresponding value of ionospheric critical frequency; the sloping line through the origin is the cut-off frequency for the lowest order Pc1 mode propagating in the ionospheric duct. (After F. N. Manchester)

1.6 Pc1 "Pearl" Theories

Much theoretical effort has been put into the understanding of the mechanism of the Pc1 "pearl" signals. In order to explain the excellent point conjugacy of these signals, all of the proposals have involved something - either bunches of particles or packets of MHD waves - travelling between conjugate points along the geomagnetic field lines. The first of the models which attempted to explain Pc1 used "fast electrons"[33] or "fast protons".[34,35] In these models bunches of particles oscillate rapidly between conjugate points. The particles can be thought of as bouncing along a field line between reflection points above the two conjugate regions. The reason for this bouncing motion is connected with two facts concerning particles trapped in the magnetic field of the earth: 1) The particles have a constant total energy, and 2) along the particle path, the field is a minimum over the equator (i.e., the field lines are far apart) and the field increases as one goes along a line toward either pole (i.e., the field lines come closer together). The oscillatory bounce motion along a magnetic field line is exactly analogous to a swinging pendulum, which also has constant total energy. In the case of the pendulum, the energy is divided between the kinetic energy (the velocity) and the potential (the height of the pendulum above the bottom of its swing). For a pendulum the kinetic energy is "traded off" for potential energy. The velocity is maximum at the bottom of the swing and the potential energy is zero. At the top of the swing, the velocity is zero, and the potential energy is a maximum. For the oscillating particles in the earth's field, the total constant energy is divided between two types of kinetic energy. One is the velocity of the particle along the field line, which is analogous to the velocity of the pendulum. The other seat of energy is the circular motion of the particle around the field line. This "cyclotron energy" is proportional to the magnitude of the magnetic field in which the particle finds itself. As we have said, the field increases as one goes poleward. Thus, as the particle moves from the equator toward the pole, it transfers energy from its linear velocity and puts it into "cyclotron energy." When the velocity along the field line reaches zero and all of the energy is in the cyclotron mode, the particle "mirrors" and reverses its travel along the field line.

In the case of Pc1 oscillations the frequency within the "pearl" was thought to be characteristic of the bounce frequency. The space between the "pearls" was associated with the east-west movement of bunches of particles around the world - each "pearl-pearl" spacing represents the time necessary for the bunch to circumnavigate the world confined to the surface of a particular L-shell. Such an east-west movement would be the result of an electric field postulated to be present in the magnetosphere. It can be shown from elementary electrodynamics that such an east-west motion results for particles bouncing along north-south magnetic field lines in the presence of an electric field perpendicular to the surface of the earth. There are, in fact, theoretical schemes of magnetospheric currents which would yield such fields. The problem with this model is that it does not predict the well-known 180° shift in amplitude. In other words, it does not account for the fact that, as Figure 12 shows, "pearls" are not received simultaneously at conjugate points but are spaced exactly between each other. Thus, Jacobs and Watanabe[36] proposed a "slow proton mode," in which the spacing between "pearls" corresponded to the bounce. The frequencies within the "pearl" (Pc1) were said to be excited as resonant MHD oscillations in the lower magnetosphere. Unfortunately, this model gives the wrong dependence of Pc1 frequency with latitude, predicting an increase in the frequency with latitude. Finally, Jacobs and Watanabe[37] proposed the "MHD wave packet" theory, in which the space between "pearls" corresponds to the bounce time of the wave packet and the Pc1 frequencies within the "pearl" correspond to the frequencies of the wave packet. This model seems to fit all the observed data.

The explanation of the generation mechanism of the MHD waves required in the Jacobs-Watanabe model has been one of the notable successes of micropulsation theorists. The generation mechanism is called the "ion cyclotron instability model." It was first proposed by Cornwall[38,39] in 1965. The basic ideas of the theory are that in the outer magnetosphere (L=4-10) the magnetically trapped particles, primarily protons, find themselves in a region in which they are moving supersonically with respect to the Alfvén velocity of the region. This causes MHD waves to be emitted at the frequency of the local cyclotron resonance (see p. 23). These circularly polarized waves travel down the field lines, as predicted in section 1.4, and are mirrored back. When they pass through the region of instability again, they are amplified and proceed to the opposite conjugate region where the process is repeated. This mechanism not only accounts for generation and amplification but also accounts for the rising tone spectrum, which is often observed in Pc1 "pearls." The idea of being able to use - free of charge - a stimulated amplification in the magnetosphere is one of the characteristics that makes the use of micropulsation mechanisms and modes very inviting for a communication system.

One of the most complete and successful treatments of the cyclotron instability amplification mechanism has been given by Criswell.[40] He applies the theory to an observationally-justified form of the proton plasma distribution and one in which the energy distribution is consistent with available satellite data. Further, he uses a real magnetosphere in the sense that the distorting effects of the solar wind on the shape of the magnetosphere are included. This is necessary when considering regions more distant than about L = 6, since the solar wind distortion dominates the character of the field and the plasma beyond that distance. A schematic picture resulting from IMP-1 satellite data is shown in Figure 18. Using this very complete model Criswell does, in fact, find that maximum amplification of left hand circularly polarized waves (the kind required for field line guidance) takes place in the 2-5 Hz region of the spectrum. He also finds quantitative agreement with the latitude variation of Pc1 "pearl" frequency and the correct correlation with the geomagnetic disturbance index, Kp. He is also able to account for the magnitude of the observed proportionality of "pearl" repetition frequency with the signal frequency within the "pearl."

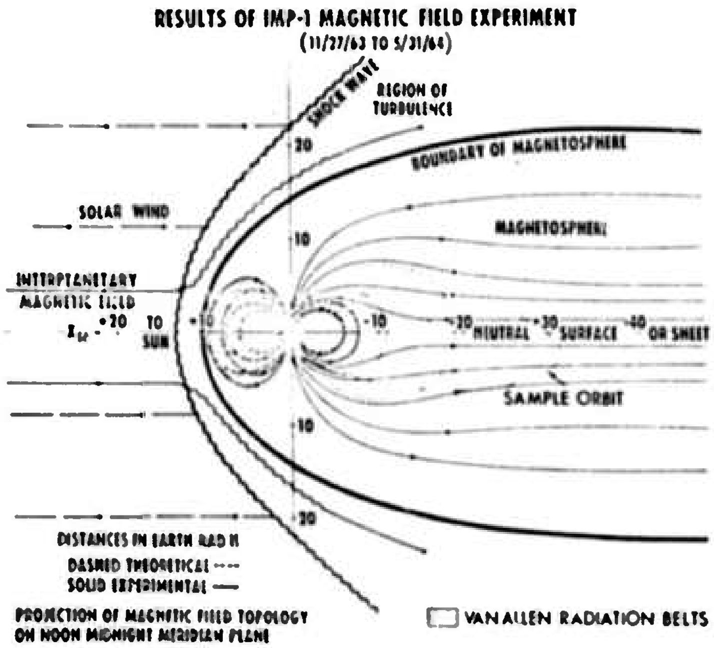


FIGURE 18

Configuration of Geomagnetic Field Lines
in the Magnetosphere Showing the Effects of the Solar Wind
(After Ness, et. al.)

In summary, then, it can be concluded that the amplification of Pc1 "pearl" signals is rather well understood. No one theory, however, yet accounts for all types of Pc1 observations, and there remain some questions as to exactly how the cyclotron instability mechanism is applicable to all data.

2.0 SOVIET RESEARCH

2.1 Historical Introduction

In this section we shall briefly review some of the background of Soviet programs related to the study of high frequency micropulsations. The U.S.S.R. operates a permanent network of about 30 magnetic observatories in the U.S.S.R., plus several more in Antarctica and on drifting ice floes in the North Polar Region. All these stations are capable, or could easily be made capable, of measuring high frequency micropulsations signals. The number of stations has grown steadily from the five which existed at the time of the Russian Revolution. In addition to satellite-borne instrumentation, the Soviets have operated geomagnetic stations from barges on inland waterways and from the famous, specially built (1957) non-magnetic oceangoing ship Zarya. Through international agreements, the Soviets share the operation of a number of magnetically conjugate station pairs. These pairs, the most well-known of which is Sogra-Kerguelen, as we have seen, have contributed enormously to the understanding of Pc1 and Pi1 signals. We shall discuss the conjugate point program in greater detail elsewhere.

There are two institutes, both under the U.S.S.R. Academy of Sciences, which are responsible for a large part of the Soviet study of high frequency micropulsations. The Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN) was established in 1940, and though its primary interests appear to be higher in the electromagnetic spectrum, it has contributed a large part of the Soviet effort. The reliable, rugged magnetic variometers designed by N. Bobrov of IZMIRAN have been used at nearly all Soviet magnetic stations. In addition, IZMIRAN operates the ship Zarya. IZMIRAN's primary interest in micropulsations is probably as a diagnostic tool in understanding the geomagnetic storms which disrupt conventional high frequency communications. A stated interest in the communications possibilities at frequencies in the micropulsation range has been lacking. IZMIRAN also oversees the operation of two other institutes which are involved in high frequency micropulsation research. They are the Siberian branch of IZMIRAN (Sib-IZMIRAN) and the Polar Geophysical Institute (PGI).

The largest and most active group in the U.S.S.R. involved in high frequency micropulsation research is the Institute of Terrestrial Physics imeni O. Yu. Shmidt, also known as the Institute of the Physics of the Earth (IFZ). Most of the research in this area at the Institute is led by V. A. Troitskaya. No study of micropulsations would be complete without mentioning the impetus that Mme. Troitskaya has imparted to the study of micropulsations both in the Soviet Union and abroad. Her publications alone, with Soviet colleagues, and with French colleagues involved in the Sogra-Kerguelen conjugate program, have probably produced the largest single body of experimental data on high frequency micropulsations. In general, the thrust of most of the publications of the Institute have been toward the use of micropulsations as diagnostic tools, and like the IZMIRAN work there is no professed program on the use of micropulsation modes for communications purposes.

In addition to these two organizations, many other scientific research institutes and university groups contribute to Soviet studies on high frequency micropulsations. Among the more important academic institutions are Moscow State University, Leningrad State University, and Gor'kiy State University. Active research institutes include the Arctic and Antarctic Institute of the U.S.S.R. Hydrometeorological Service and various organizations involved in space-related or plasma physics research.

The Soviet program of conjugate point studies is the most extensive in the world. Much of it involves the Omega Project, which is a joint program of studies carried out with the French, who possess many of the islands, including Kerguelen, in the South Indian Ocean. All of the islands are conjugate to points in the U.S.S.R. The name of the project derives from the shape of the Greek letter Ω which resembles a field line connecting two conjugate regions. The program was initiated in 1962, using Kerguelen and the already established station at Borok. By 1964, a magnetic observatory had been set up at Sogra in the Archangel Oblast. Sogra is very close to the exact conjugate point* of Kerguelen (L=3.6). As part of the program of determining the spatial extent of conjugate effects, many observatories have been set up in the vicinity of Sogra. This support network is shown in Figure 19. Eventually, other conjugate stations pairs were set up under the program. Among them are Dolgoshchel'ye - Heard Island (an Australian possession used with the permission of the Australian Government) and P'skov - Ile de l'Est (French) in the Crozet Islands. The Dolgoshchel'ye-Heard station (L=4.5) is on the same geomagnetic meridian as Sogra-Kerguelen, and the P'skov-Ile de l'Est station (L=2.5) is the geomagnetic west of Sogra-Kerguelen at lower geomagnetic latitude. Interesting types of correlation experiments, impossible anywhere else in the world, may be performed using this extensive network. Many experiments on conjugate phenomena other than high frequency micropulsations have been performed at these stations. IZMIRAN investigators have studied conjugate auroral and ionospheric events; naturally occurring, very low frequency (VLF) phenomena, such as "whistlers" and so-called "VLF emissions"; particle and x-ray precipitation; and geomagnetic storm characteristics. The research has been carried out both at ground level and using balloon and sounding rockets to carry particle and x-ray recording equipment above the atmosphere. An instrumented barge was sailed down the Northern Divina River in an experiment attempting to discover the spatial extent of the conjugate region. Relating directly to the question of high frequency micropulsations, Troitskaya of IFZ and R. Gendrin of the French National Center of Telecommunications Research (CNET) and the Groupe Recherches Ionosphériques (GRI), and their co-workers, have published a continuing series of papers on Pc1-Pi1 morphology as deduced from conjugate point data. Reviews of the conjugate program have been written by Zhulin[41] of IZMIRAN and Troitskaya[42] of IFZ.

*The location of the exact conjugate point may vary in time by about 100 kilometers, but nearly all conjugate effects are unaffected by the error this introduces.

FIGURE 19

Network of Stations Used in Conjunction with the Sogra-Kerguelen Conjugate Pair in Order to Determine the Extent of the Conjugate Region (After M. I. Pudorkin, V. A. Troitskaya, Ya. I. Fel'dshteyn)

In the next sections we shall review the recent Soviet research relevant to high frequency micropulsations. In addition, we shall mention some papers on lower frequency work which may be applicable to the understanding of the high frequency signals and, therefore, important in the problem of communications.

2.2 Instrumentation

Before proceeding to a discussion of the experimental micropulsation data we should briefly discuss the state-of-the-art of magnetometry in the U.S.S.R. As we have noted, V. N. Bobrov and his associates at IZMIRAN have developed a quartz magnetic variometer (a variometer measures changes in the field) which is used at many Soviet geophysical stations. Bobrov has published the results of his investigations with the device continuously since about 1962. The basic element used in the quartz magnetometer is shown in Figure 20. The actual magnetometer constructed with this sensor is shown in Figure 21. According to Bobrov,[43] instruments like that shown in Figure 21 were first fabricated and tested in 1966. The device includes a mechanism to compensate for changes in tilt of the device which allows for easy operation under adverse environmental conditions in both fixed and mobile operations. One of the drawbacks of this type of magnetometer is that changes in the field perpendicular to the field component being measured may affect the accuracy of the instrument. Burtsev and Bobrov[44] have analyzed this situation in detail and have shown how one may compensate for that effect. In a further improvement, Bobrov and Burtsev[45] have designed a Z-axis (vertical) component instrument where the position of the zero is independent of the tilt of the system. It thus becomes possible to correlate changes in the vertical field between separate and independent magnetic stations. The widespread use of the Bobrov magnetometer in geophysical observatories attests to its ruggedness and simplicity of operation.

A review article[46] basically concerned with measuring magnetic fields in sea-borne systems gives a good picture of the state of Soviet magnetometric instrumentation. In Table 2 below we list some of the Soviet

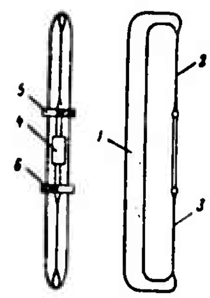


FIGURE 20

Astatic Bobrov Quartz Element: 1 All Quartz Frame, 2 and 3 Quartz Tension Wires, 4 Quartz Mirror, 5 and 6 Anti-Parallel Permanent Magnets. (After V. N. Bobrov)

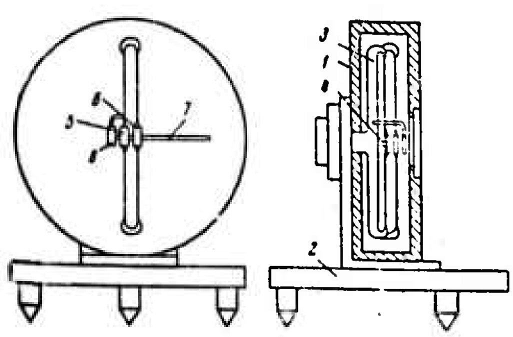


FIGURE 21

Quartz Magnetic Variometer: 1 Hernetically Sealed Having 2 Base with Leveling Screws, 3 Quartz Sensing System, 4 Permanent Magnet, 5 Quartz Mirror, 6, 7 Orthogonal Sensing System, 8 Stationary Mirror for Orientation Monitoring. (After V. N. Bobrov)

TABLE 2

SOVIET MAGNETOMETERS FOR MARINE RESEARCH

ORGANIZATION	TYPE	LIMITS OF MEASUREMENT	SENSITIVITY	RECORDING METHODS	FEATURES
Institute of Oceanography	Flux gate ΔH, ΔZ	$10^5\ \gamma$	1γ	Analog Plot	Operates in towed gondola.
IZMIRAN	Flux gate ΔH, ΔZ	$5\times10^4\ \gamma$ for H $7\times10^4\ \gamma$ for Z	50γ	Analog Plot	Operates in towed gondola at 25 m depth
Marine Hydrophysical Institute, Acad. Sci. UkrSSR	Flux gate ΔH, ΔZ	$5\times10^4\ \gamma$	30γ	Analog Plot	Operates in towed gondola at 40m depth
All-Union Scientific Research Institute of Geophysics	Proton Precession	$3.5\text{-}5.0\times10^4\gamma$	2.5γ	Direct digital readout and analog plot	

magnetometers reviewed in that article. ΔH means the device measures changes in the horizontal field, and ΔZ means the device measures changes in the vertical component of the field. The Soviets have also demonstrated the ability to fly sensitive proton precession magnetometers aboard aircraft.[47] They have learned how to cope with the vibrational problems introduced by such an environment[48] and how to process the data to remove the effects of aircraft noise.

Although the devices shown in Table 2 are primarily for use in mapping the earth's main field, sea floor magnetic anamolies, and mineral deposits, they are included along with the quartz magnetic variometer to illustrate the excellent Soviet capability in magnetometric measuring systems. Most important, they illustrate the capability to construct and operate devices for use under very rugged conditions far from the design and fabrication laboratory.

It should be noted that the magnetometers discussed above are required for low frequency magnetic field measurement. They may be used at Pc1 frequencies, but are not necessarily required. In the Pc1 domain it is still possible to use "induction magnetometers" which are really large-loop antenna systems. The signal developed across such a loop is $L\, d\phi/dt$ where L is the inductance of the loop and ϕ is the magnetic flux through the loop (the magnetic field multiplied by the loop area). The signal is therefore proportional to the <u>rate of change</u> of the field, not to the magnitude of the field itself. The device is, therefore, a variometer. If magnetic field signal is assumed to be a pure sine wave, $A \sin(2\pi ft)$, where A is its amplitude, f its frequency, then $d\phi/dt \propto f$ and it is apparent that the output signal from the induction magnetometer is proportional to the signal frequency. Hence, since the signal drops off at low frequencies this device is restricted to only high frequency micropulsation signals.

2.3 High Frequency Observations

One of the most detailed analyses of the morphology of Pc1 "pearl" pulsations was reported by Troitskaya et al.[49] in 1971. They carried out detailed analysis of large amounts of observational data. The study examined the relationship between "pearl" spacing and Pc1 frequency and also the relationship between "pearl" spacing and change of frequency within "pearls" (e.g., whistlers or rising tones). They also examined changes of Pc1 frequency with variations of magnetic activity and the relationship between "pearl" amplitude and spacing. The new results of these experiments seem to infer that Pc1 may occur on several L shells simultaneously and that this may be responsible for some of the dispersive effects which are observed. This idea seems to contradict previously-held conclusions that Pc1 "pearl" generation was localized in L value in its generation region.

The Soviets have also done several of the correlation type experiments similar to those referenced in section 1.3. Vinogradov et al.[50] observed the polarization of Pc1 events simultaneously at Sogra and Irkutsk. They have found twice a daily rotation in the direction of polarization of Pc1 signals, once between 5-8 hours local time and again between 17-20 hours local time. Both the stations used in this experiment may be considered mid-latitude with respect to "pearl" generation. That is, they are at L values less than 4-6 which means that signals reach them by the ionospheric duct mode. Therefore, it is not clear whether such polarization shifts represent changes in the ionospheric duct or in the signal as it is generated in the magnetosphere. A careful experiment[51] on the ionospheric propagation of Pc1 involving a network of five stations in the Soviet Union has shed further light on the question of the effects on the signal of ionospheric propagation and adds considerably to the knowledge of which characteristics of Pc1 are controlled by ionospheric propagation and which are due to processes in the generation region. The author concludes that none of the circularly polarized energy from the primary MHD wave propagating down the field line from space can reach the ground. Instead, according to Baranskiy, the author, a secondary MHD acoustic source of <u>linear</u> polarization is excited in the ionosphere. However, elliptical polarization is observed on the ground due to dispersive effects which introduce different phase shifts at the different frequencies present in the original magnetospheric signal, thereby producing a superposition of linear signals in the proper phase relationship to yield an elliptically polarized resultant. This explanation of the relationship between the magnetospheric and the ionospheric Pc1 signal is consistent with the fact that on the ground the ellipse is observed to rotate its major axis in the direction parallel with the magnetic meridian as one goes from magnetic pole to magnetic equator. This is understood to be preferential propagation for the linear polarized signal with its propagation vector along the geomagnetic meridian. This work would also imply that the diurnal changes in polarization observed in this experiment and that of Reference 50 are the result of changes in the source of Pc1 "pearls" and not in the ionospheric duct.

Two papers treat the longer term correlations of Pc1 "pearl" events. F. I. Sedova[52] has demonstrated the place of Pc1 events in the "family" of events which make up a geomagnetic storm. He claims to have shown that all magnetic storms can be divided into a number of different geophysical events and that Pc1 has a regular place within this "family." Generally, Pc1 events are found to occur on the day preceding a geomagnetic storm or under certain solar conditions preceding the storm on the day of storm commencement. According to Sedova, Pc1 may then be viewed as a predictor of geomagnetic disturbances to come. This analysis is somewhat consistent with past experiments since it does say that Pc1 occurs on quiet days (i.e., before the storm) but there is not general agreement that Pc1 precedes every magnetic disturbance. In the other paper, Matveyeva et al.[53] have taken the previous work by Fraser-Smith and Matveyeva on the correlation between solar activity and Pc1 (see Section 1.3) and have attempted to make long-range forecasts based on expected solar activity of the frequency of appearance of Pc1 through the year 1977. If the expected 80 percent reliability of this forecast is realized, it should be of great help to experimenters planning expensive, large-scale Pc1 experiments.

As we have pointed out in Section 1.3, there is a great deal of Soviet interest in the IPDP pulsations which appear to be a combination of Pcl and Pil and which also appear to be characteristics of magnetic storms. The IFZ group has been very active in this area of research and they have made progress in understanding how IPDP is related to storm events. Specifically, Troitskaya and Gul'yelmi[54] have associated IPDP with the injection of low energy protons into the magnetosphere. They have shown that the frequency of the pulsations is proportional to $1/\sqrt{\varepsilon}$ where ε is the particle energy. They have further shown that in a reasonable model of a precipitation event one would expect the high energy particles to precipitate first, followed by a subsequent decrease in energy. This would imply a rise in frequency (decrease in period) as is experimentally observed. Mal'tseva et al.[55] analyzed 83 IPDP events recorded at Borok between 1961 and 1964. In this experiment they examined the correlation of IPDP with the various events of a geomagnetic storm. They have been able to conclude that IPDP is due to the cyclotron instability mechanism. The particles involved are protons with several tens of kilovolts of energy. During a storm these protons are precipitated preferentially into the evening side of the magnetosphere and the IPDP signal is generated by the cyclotron instability mechanism.

We have already mentioned in Section 1.5 the work of Dubrovskiy and Kramarenko[56] in discussing the ionospheric filter problem. We should say here that the data they have collected on the entire spectrum of micropulsations from 10^{-4} Hz to about 1 Hz is only partially Soviet in origin. In fact, the satellite data used in this work is entirely Western. We nonetheless feel that the gathering and analysis of this wealth of data is a significant Soviet accomplishment since it unifies a large part of the available information on magnetospheric and earth-ionospheric modes. Any attempt to discover new modes or use the known ones for communications purposes would rely heavily on this compendium of data. The authors do not intend that the fine structure of the power spectra shown in Figure 9 be evident from this report, but they do claim that the gross characteristics of the background spectrum and the effects of the earth-ionosphere waveguide cut-off frequencies are evident in the data.

2.4 Magnetospheric Diagnostics

We have stressed that the major stated thrust of Soviet micropulsation research is in the area of ground based diagnosis and prognosis of the state of the magnetosphere. Even though the conditions of the magnetosphere must be obtained indirectly through the adoption of magnetospheric theories and models, the simplicity of the data gathering apparatus and its extreme low cost in men and material when compared to direct data gathering by sounding rocket or satellite makes the diagnostic problem a very attractive area of research. Two excellent surveys by Troitskaya and her colleagues, one in the semi-popular journal Priroda[57] (Nature) and a more detailed article in the Vestnik[58] of the Academy of Sciences detail the goals of micropulsation analysis for diagnostic purposes. According to Troitskaya the following problems are addressable through the study of micropulsations.

1. The estimation of the concentration of cold plasma in the magnetosphere and the estimation of the position of the magnetospheric boundary.

2. The estimation of nonstationary processes in the radiation belt:

    a. The position of the outer boundary of the radiation belt.

    b. Variation in particle density in the external belt.

    c. The estimation of the intensity of the electrical fields in the magnetosphere.

3. The estimation of the energy and density of particle fluxes in the magnetosphere which are responsible for the excitation of Pcl "pearl" type pulsations and the localization of the area of their generation.

4. Estimation of the solar wind parameters:

    a. The velocity.

    b. The direction of the interplanetary field in the plane of the ecliptic.

    c. The extents of heterogeneities in the solar winds structure.

Troitskaya points out that other ground based observables such as visual and radio aurora and naturally occurring VLF emissions supply data to supplement the micropulsation information. In this work the data on Pc1 assumes great importance since the relatively short wavelength and spatial localization of Pc1 make it an excellent probe. Since the field line guidance of Pc1 signals and, thereby, the signal path is also rather well understood, the conjugate point data also assumes a very important role in magnetospheric diagnostics.

As examples of the details this kind of work can produce, we cite two illustrations. Kalisher and Matveyeva[59] have been able to deduce the scattering of magnetospheric protons by the Pc1 MHD wave packets themselves. The experimental data used are the bandwidth of the Pc1 signals, the average frequency of the signals, the amplitude of the pulsation and the cyclotron frequency of the plasma at the equatorial plane of the L-shell on which the signal is travelling. In order to know the cyclotron frequency one must have estimates of the particle density and magnetic field in the generation region (see Section 1.4 for a discussion of the cyclotron frequency). In order to estimate the true magnetospheric amplitude of the pulsation one must estimate the losses due to ionospheric transmission of the signal and the change from MHD to EM wave. All of this information is then incorporated in a scattering theory and finally the quantity of scattering may be calculated. Clearly, there are many uncertainties in the result but, as we continue to observe, it is much cheaper than performing an on site experiment with a satellite. Even with this complex calculation procedure the magnitude of the scattering is found to be of such a high order that it allows the authors to conclude that one of the major mechanisms for removal of particles from trapped radiation belts is probably the scattering of these particles from MHD waves. The second example we wish to cite illustrates how the diagnosis problem may be worked from another aspect. Gul'yelmi[60] has calculated the spectrum of Alfvén oscillations in the magnetosphere. He mathematically demonstrates how this spectrum can be used to determine the equatorial value of the plasma concentration. In this case, the experimental micropulsation data used are the periods corresponding to the observed peaks in the long wave Pc3-4 spectrum. The results of the density calculation are then compared to existing satellite data in which the plasma concentration in the region of interest was directly measured. The results are found to be in close agreement. Thus, in effect, the diagnosis problem worked backwards has been used to confirm the theory which Gul'yelmi has proposed. The possibility of coincidence in these results cannot, however, be excluded. An interesting sidelight is that the results for the plasma density as calculated by Gul'yelmi and as also observed by satellite is several times higher than what is obtained by the older technique of analyzing Pc1 "pearls" by dispersion techniques. This is a good example of how the indirect techniques used in the diagnostic problem may produce conflicting results.

2.5 Wave Theory Research

Soviet investigators have performed many studies extending the work of Dungey and others on the wave modes of the magnetosphere. They have applied numerical techniques to the solution of the mode equations 1.4.12 and 1.4.13. We have already referred to the work of Gul'yelmi[61] of IFZ in the previous section, in which he calculates modes of the magnetosphere. He reduces the problem to a one dimensional calculation of resonant modes. In his work, he notes the unreality of the axial symmetry assumption made in arriving at the simplified wave picture presented in Section 1.4. He makes note of the experimental fact that micropulsations are indeed localized in longitude, and he relaxes the axial symmetry restrictions by allowing oscillations of individual lines of force. He does, however, retain the dipole field approximation. Gul'yelmi states that the success of his method in predicting the proper plasma density may be regarded as the confirmation of the fact that micropulsations are, in fact, MHD oscillations of the magnetosphere.

The toroidal oscillations (equation 1.4.12) have been solved in detail by Bryunelli and Namgaladze[62]. In their solution, they assume a power law fall off of the plasma density, and they have retained axial symmetry. They have solved the problem for both the dipole field case and the so-called "Mead model" of the field, which is a simple field model including some terms beyond dipole. They have used their results primarily in addressing the diagnostics problem. They employed the observed Pc3-5 resonances and calculated the resultant plasma densities. D. S. Kotik[63] of Gor'kiy State University has considered the problem of the effect on MHD waves of passage through a region of large gradient in Alfvén velocity. The region in which this occurs is at an altitude of 2000 - 3000 km. As we have seen in the work of Prince and Bostick (Section 1.5), this region of space above the ionosphere plays an important role in influencing the spectral response of the magnetospheric cavity. Kotik calculates reflection and transmission coefficients for the process of wave impinging on this region from above. The process also allows for the transformation of some of the wave disturbance from transverse to magnetoacoustic (compressional) modes. The computations are performed for the limiting cases of magnetic field perpendicular to the boundary (i.e., at the pole) and field parallel to the boundary (i.e., at the equator). The appearance of magnetoacoustic modes is the new feature of this work. It is not evident that the actual existence of these modes in nature has as yet been demonstrated. We do, however, emphasize that the prediction and discovery of new modes could prove very important in the communications application of micropulsations.

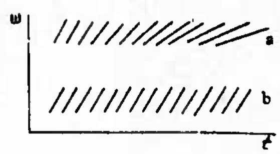
It will be recalled, that in the derivation of the wave equations of Section 1.4, one of the assumptions was that the magnetosphere was a perfect conductor. Van'yan and Yudovich[64] have investigated the question of field line guidance of toroidal waves under a relaxation of this assumption. They assume that the complex dielectric constant, which is related to the conductivity, is large but not infinite. This approximation corresponds much more to reality. They find that field line guidance still results from their calculations, although some propagation transverse to the field line does take place. The important result is that the field decreases at least in inverse proportion to the distance from the field line on which the source is located. Unfortunately, this result has been derived for the case of frequencies much lower than the proton cyclotron frequency, which, as we have seen, is approximately one Hz, and, therefore, the results are not directly applicable to signals in the Pc1 frequency domain. Extension of the work to the high frequency region, near the cyclotron frequency, has not yet been reported. As with the work of Kotik, discussed above, this theoretical work demonstrates Soviet activity in a subject area of great importance to any communications system involving the field guided propagation of signals.

Soviet authors have considered the effect of the ionosphere on micropulsation signals from a slightly different aspect than that discussed in Section 1.5. There has been a group of papers addressing the ionospheric problem from the point of view of considering the ionosphere as a thin sheet of high conductivity, located above the surface of a conducting earth. This view stresses that the impinging micropulsations set up electrical currents in this sheet, which in turn generate the fields that are detected on the ground. This picture is used to discuss the effect of the ionosphere on the micropulsation signals reaching ground level. The results of these investigations bear on the apparent propagation velocity of signals between points on the earth and on the effective attenuation suffered by the signal in passing through the ionosphere region. In the strictest sense, the study[65] bearing on propagation velocity is applicable only to the longer period micropulsations. The work concludes that for realistic values of earth conductivity there is <u>no</u> phase shift in the signal during propagation from high to low latitudes. This means that there is no time delay between signal reception at separated sites. This theory replaces old theories, which gave values as low as 30 km/sec for the propagation of the signals. This new work is consistent with experimental data on Pc2-5 (see Section 2.7). These results should not be confused with the results of Manchester and others discussed in Section 1.5. In that work signals travel in a duct formed by the F_2 region of the ionosphere. Davidov and Snegurova,[66] in their calculation of the attenuation effects have found that the attenuation is dependent on both frequency and the ground conductivity below the ionosphere. They find that the attenuation is greatest at the high frequencies in the Pc1 domain. Fortunately, even in this frequency range, for the worst case the ionosphere weakens the impinging field by not more than a factor of 5, which corresponds to about 7 decibels in signal strength. At these high frequencies, the conductivity of the ground plays an important role in determining the amplitude and phase shift of the signal. There is, as yet, no experimental data which directly compares Pc1 amplitudes recorded at sites over high conductivity material, such as seawater, and low conductivity earth.

Such a comparison would be necessary to confirm the results of these calculations. Although the seven decibel signal loss in passing through the ionosphere is a significant attenuation, it is not great enough to nullify the interest in communications at these frequencies with micropulsation modes.

2.6 Pc1 Generation and Amplification by Cyclotron Instability

Soviet authors have published an important series of papers which apply the cyclotron instability mechanism discussed in Section 1.6 directly to the problem of Pc1 morphology. The basic question which is addressed is: Can the cyclotron instability theory be applied to all of the various observed forms of the Pc1 "pearl" structure and, if so, what is implied about the mechanism in each case? We recall that the two basic sonagraphic patterns for Pc1 "pearls" are as shown in Figures 22a and 22b, where a is the hydromagnetic whistler case and b is the parallel rising tone case. Complex structures such as that shown in 22c are also seen. Until this series of papers it had been assumed that different mechanisms were responsible for each of these cases. In 1969 Feygin and Yakimenko[67] published a paper which showed how the various Pc1 morphologies could result from the same cyclotron amplification mechanism. They also reported[68] this work in expanded form at the International Association of Geomagnetism and Aeronomy meeting of micropulsation researchers later that same year. In their work they first display the so-called "increment equation" which defines the quantity γ. This parameter expresses all of the characteristics of the cyclotron amplification process. It has the property that it must be greater than zero for amplification to occur. Likewise, it depends on the fact that the streaming high-energy particles which are responsible for amplification are anisotropic in energy distribution. γ depends on the cyclotron resonance of the particles in the amplification region, the amount of anisotropy, and, of course, on the frequency and wavelength of the signal to be amplified. Basically then, γ depends on the properties of the streaming unstable particles and the characteristics of the signal to be amplified. This dependence is at the heart of their explanation of the various Pc1 morphologies. From the expression for γ



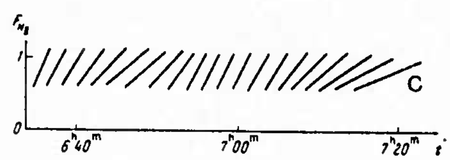


FIGURE 22

(a) Hydromagnetic Whistler
(b) Pure, Parallel Rising Tones
(c) Composite Pc1 Signal as Often Observed
(After F. Z. Feygin, V. L. Yakimenko)

the quantity $\alpha = -\partial^2\gamma/\partial k^2$ is defined where k is the wave vector and $|k| = 2\pi/\lambda$, where λ is the wavelength of the signal. Also defined is the quantity $\beta = \partial^2\omega/\partial k^2$ where ω is the angular signal frequency. Recall that the relationship between ω and k is the dispersion relationship which we have discussed in Section 1.4. Feygin and Yakimenko have shown that an initial broadband magnetic disturbance - that is, one which initially contains a very wide spectrum of frequencies - is "filtered" by the amplification quantity γ and the dispersion relationship to yield the various spectral forms of Pc1 "pearls". The simplest case is for γ = constant. At frequencies below the cyclotron frequency and where the period of the carrier frequency (the frequency within the "pearl") is greater than the frequency of bouncing between conjugate points, they predict hydromagnetic whistlers (Figure 22a) with the following characteristics:

1. The dispersion effect filters the broad band generating pulse to make it become a highly monochromatic rising tone which for the approximations here will be nearly linear with time.

2. The width in time of the pearl should increase as $t^{1/2}$.

3. The slope of the "pearl" spectrum should decrease from "pearl" to "pearl" as t^{-1}.

The other cases of spectral shapes occur for differing conditions on $\bar{\alpha}$ and β. $\bar{\alpha}$ is a time averaged value of α in the amplification region. These results require that $\bar{\alpha} \gg \beta$. They then relax the condition that γ is constant which physically means that the amplification is permitted to change with time. The authors find that $\bar{\alpha}$ cannot decrease <u>faster</u> than t^{-1}. If $\bar{\alpha}$ decreases more slowly than t^{-1}, the slope of the "pearl" structures can decrease less rapidly than t^{-1}. If $\bar{\alpha}$ decreases as $\sim t^{-1/2}$ then the slope of the "pearls" remains constant and we have the parallel rising tone case. If $\bar{\alpha}$ decreases faster than $t^{-1/2}$ the slope can actually re-erect itself as in Figure 22c. If $\bar{\alpha}$ decreases far enough so that $\bar{\alpha} \sim \beta$ then the fan shaped hydromagnetic whistler spectrum reemerges. Thus, the complex spectrum of Figure 22c may be explained as a period of constant and then decreasing $\bar{\alpha}$.

A lengthy paper[69] by the Franco-Soviet conjugate point study group repeats these derivations and then applies its results to large quantities of Pc1 "pearl" data recorded at Borok, Sogra and Kerguelen. Figure 23 shows three examples of sonagraphic records used in the study. These data illustrate all of the cases cited by Feygin and Yakimenko - whistlers, pure parallel rising tones, and alternating periods of both phenomena. For each of these plots Figure 24 shows the reciprocal of slope versus time. All of the whistler regions show the expected straight line dependence. The quantity p is the slope of the straight line sequences. The authors have shown that ω_i, the cyclotron frequency in the generating, may be determined from p and ω_o, the center frequency of the signals. No information on "pearl" spacing is required for this calculation. Figure 25 illustrates how the width of the "pearl" in time is in fact proportional to $t^{1/2}$ as the theory predicted. This prediction is only valid near the beginning of a Pc1 event. By studying the central frequency of the "pearl" events the authors have also shown that one may determine the energy of precipitating particles (protons of 10-200 kev) and that these results are in good agreement with direct experiment.

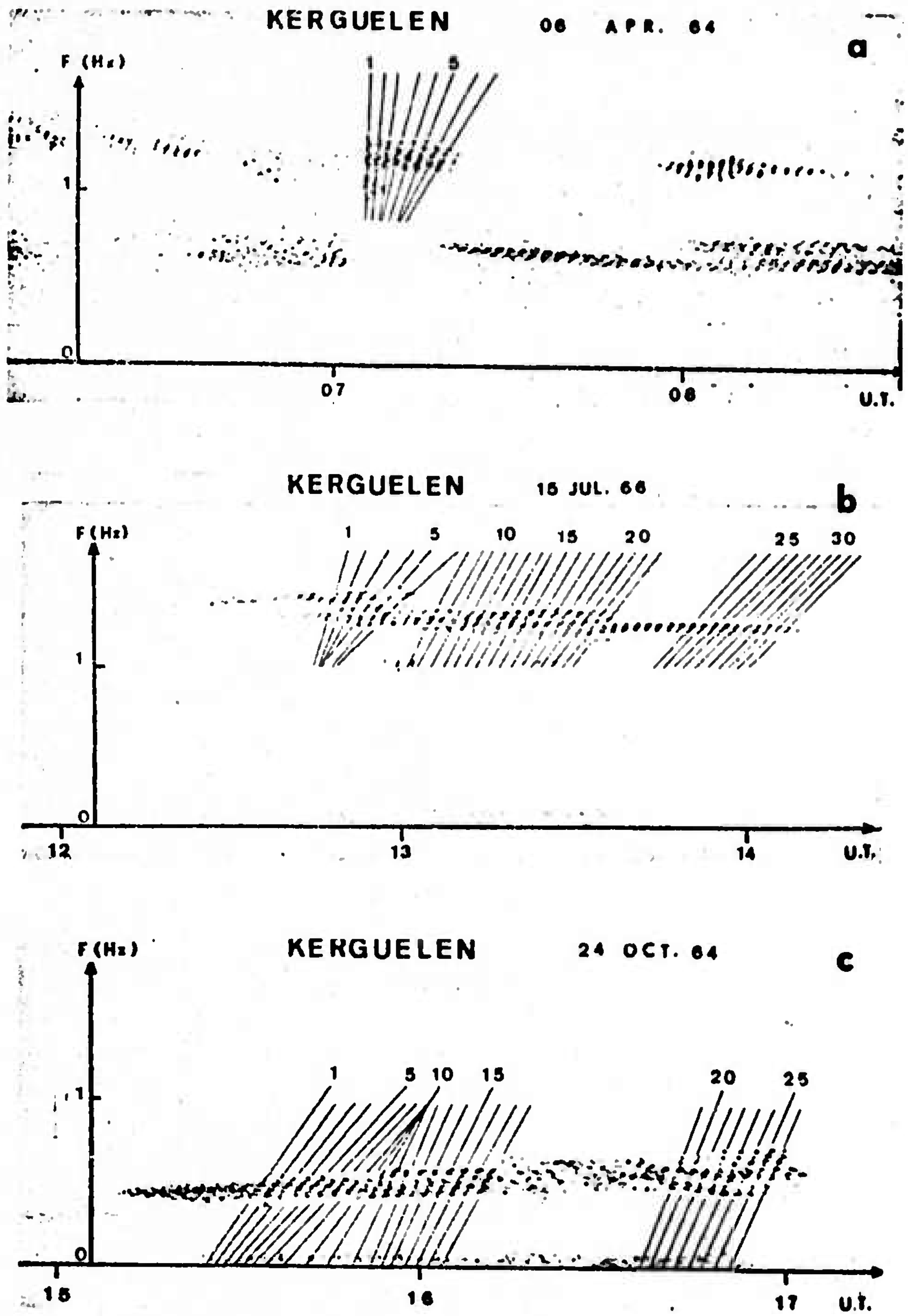


FIGURE 23

Three Examples of Pc1 Events Examined in Reference 69
(a) Pure Hydromagnetic Whistler Showing Dispersive Effects
(b) Complex Case With Increased Leaning (Hydromagnetic Whistler) in "Pearls" 1-6, 14-22, and 23-26
(c) Two Periods of Whistler (1-5, 10-18) Separated by an Abrupt Re-erection
(After R. Gendrin, et. al.)

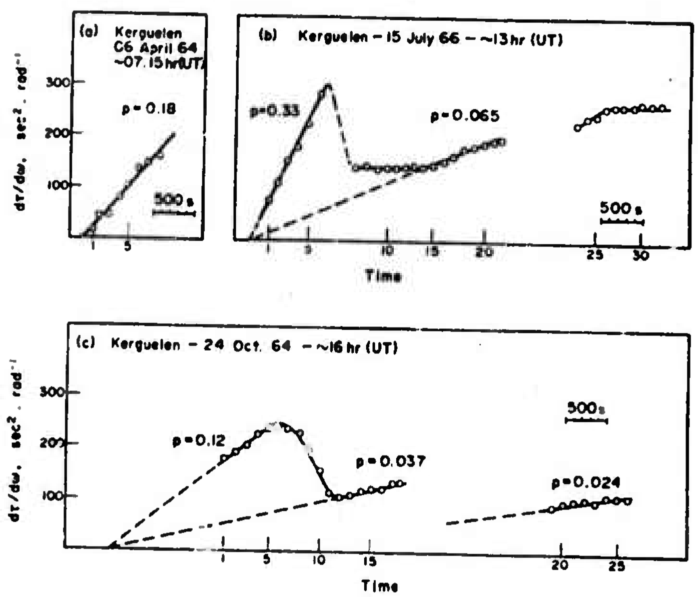


FIGURE 24

The Reciprocal of the Slopes of the Data of Figure 23 Plotted Against Time. Linear Regions Indicating Hydromagnetic Whistlers Are Evident. (After R. Gendrin, et. al.)

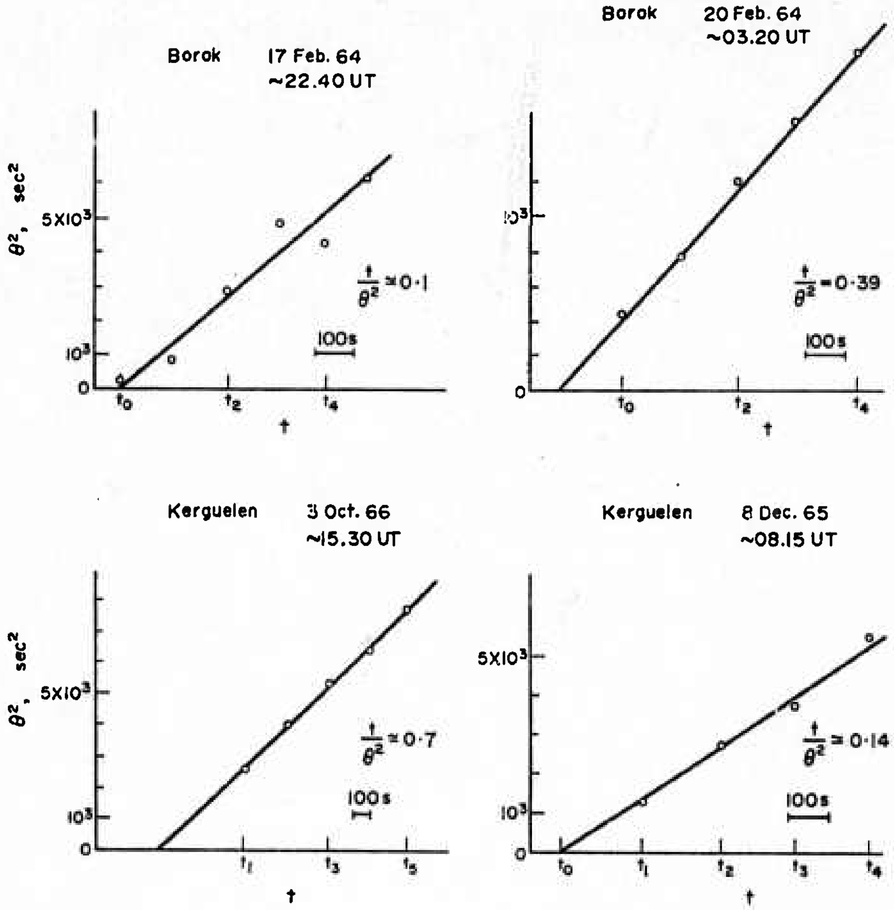


FIGURE 25

θ, the Duration of Each Wave Packet Squared and Plotted Against Time for 4 Events. The Linear Plots Indicate $\theta \propto t^{1/2}$ As Theory Predicts. (After R. Gendrin, et. al.)

2.7 Significant Experiments not in the Pc1 Frequency Domain

Here we wish to point out two papers which, though not concerned with high frequency micropulsations, may be significant in assessing the Soviet capability to investigate known Pc1 propagation modes or discover new ones which may have communications applications. Both papers are concerned with coordinated large scale networks of stations analyzing the propagation of Pc3 signals. Of significance is the extent of the networks involved. Al'perovich[70] et al. recorded simultaneous data at 24 stations across the USSR. These stations were primarily at mid-geomagnetic latitude. These stations and their locations in geographic and geomagnetic coordinates are shown in Table 3.

A similar experiment has been performed by Gudkova[71] et al. using a network of five stations. These stations are located on the same geomagnetic longitude. They were located at Belograd, Borok, Sogra, Lovozero, and Hayes Island. Experiments such as this have prompted suggestions from Soviet authors that consideration be given to instrumenting an entire geomagnetic meridian from north to south pole. Such a network, if constructed, would be unique in its ability to perform propagation studies.

TABLE 3

ϕ = Geographic Latitude λ = Geographic Longitude

Φ = Geomagnetic Latitude Λ = Geomagnetic Longitude

OBSERVATORY	ϕ	λ	Φ	Λ
Lovozero	68°	34°	65°	127°
Turukhansk	66	90	55	165
Nizhnyaya Tunguska	65	100	53	173
Salekhard	65	70	57	150
Vilyuysk	63	115	52.5	185
Sogra	63	45	57	131
Borok	55	37	51	120
Severnyy Sakhalin	54	143	43	205
Bratsk	52.5	100	41.5	170
Volga-2	52	40	47	121
Saratov	51.5	42	46	122.5
Volga-1	51.5	45	46.5	125
Bobruysk	52	23	50	105
Chernigov	50	25	48	107
Orgenburg	51	50	45	130
Ural	50	52	43.5	131
Novo-Kazalinsk	47	63	37	139
Yuzhnyz Sakharn	46	142	36.5	207
Don-1	50	37	45.5	117
Boguchar	47	37	44	119
Aral Sea	45	60	37	136
Sivash	55	50	43	110
Northern Caucarus	43	40	40	117
Ashkhabad	37	60	30	133

3.0 CONCLUSIONS

We can conclude from this review of the open literature that Soviet researchers are in the forefront in the attempt to understand the naturally occurring signals in the micropulsation spectrum. Their ongoing program of data collection and analysis is probably the world's largest effort. They have demonstrated the ability to operate large well coordinated networks of micropulsation recording stations. As we have already emphasized, the use of such networks is essential in attempting to understand the propagation characteristics of such long wave disturbances. These networks are necessary if any new modes of propagation are to be elucidated.

We should say here that, to date, Soviet as well as Western studies have reliably demonstrated only one micropulsation mode in the high frequency spectrum. That one is, of course, the field line guided L-mode wave of which Pc1 "pearl" signals are the best example. This mode would be of limited communications value since even with the addition of ionospheric ducting for propagating the signals toward the equator from high latitudes, the Pc1 "pearl" only illuminates a region of about 30° in longitudinal width around the generation and amplification region. No high frequency modes permitting low loss "east-west" signal travel have been reported.* However, if such modes do exist - and the theory presented in Section 1.4 certainly does not rule them out - it is probable that they will be discovered in nature through the analysis of data collected from large scale networks.

The Soviet scientists at IFZ and elsewhere have an excellent grasp of the cyclotron instability mechanism of Pc1 generation and amplification. The papers of Feygin and Yakimenko[72, 73] and the Franco-Soviet conjugate point group[74] have unified the various Pc1 "pearl" presentations under a single mechanism. While the work on cyclotron instability is not completed and may be modified in its detail, it nonetheless represents a great achievement for

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*See footnote, page 32.

these workers and is indicative of their deep understanding of magnetospheric processes. The use of this "free" amplification system would be a very important feature of any communications system based on micropulsation modes. Soviet understanding is also reflected by the use of micropulsation parameters as diagnostic tools for measuring and predicting the parameters near earth space.

Future Soviet efforts in high frequency micropulsations could involve the use of data collected from instrumented geomagnetic latitudes or longitudes on which well synchronized stations are placed over great distances in order to observe wave propagation parameters. Instruments such as the Bobrov magnotometer would lend themselves to use in remotely operated stations which could automatically record data on a continuous or command basis for later retrieval.

We shall conclude by noting that though no Soviet researcher professes an interest in using micropulsation modes for strategic communications purposes there are two facts which remain. First, the advantage of such a system is abundantly clear. Second, if modes appropriate to communications systems do exist, Soviet scientists, because of the magnitude of their efforts and their depth of understanding in this discipline, have an excellent chance of being both their discoverer and exploiter.

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